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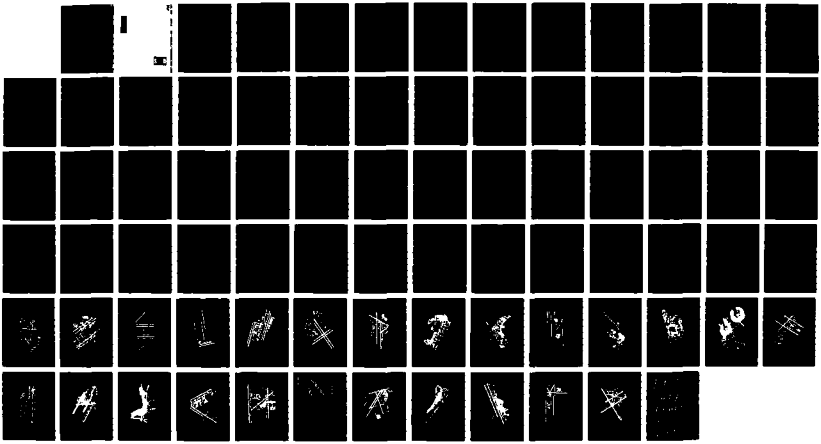

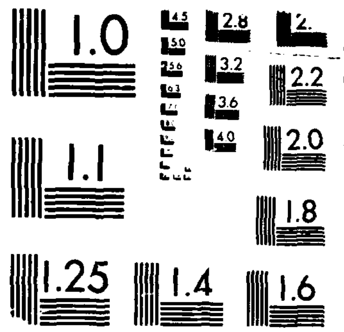

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16. Abstract

This report documents a study of requirements for an Airport Surface Traffic Automation (ASTA) system. The objective was to determine the necessary functions, establish the cost and benefits, and outline a modular system design. The highest priority function identified was an improved surface surveillance and communication system. The greatest potential for safety benefits is provided by automatic conflict alert and collision warning for pilots and controllers to prevent runway incursion accidents. Strategic and tactical planning assistance to maximize runway utilization can improve controller productivity while keeping them responsible for final decisions. The report contains a modular design for ASTA and includes specifications for a man-in-the loop simulation of the system.

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1. INTRODUCTION

This is the final report on an investigation of requirements for implementation of an Airport Surface Traffic Automation (ASTA) System.

1.1 Objective

The objective of this project was to determine the functions that would be performed by an automated airport surface control system, to establish the cost and benefits that would result from such a system, and to outline a modular design which could be simulated during a following phase of the development process.

1.2 Motivation

Airport surface control is an important element of the overall ATC system since its effectiveness can be a limiting factor in airport capacity as well as a critical component of aviation safety. The 1977 Tenerife accident in which 583 people were killed in a ground collision illustrates the potential hazard to safety. The long queues of aircraft waiting for take-off at major terminals are indicative of the interaction between surface operations and system capacity. Many of the tasks that the ground controller is asked to perform should be able to be done more easily, more reliably, and more efficiently with automation. During low visibility the controller can profit from improved surveillance. Data link and computer-generated voice communications offer the potential for reduced workload under high volume operations. A better understanding of the value of these potential benefits is needed in order to specify the direction of future research.

1.3 Plan of Attack

The work on airport surface traffic automation was initiated on 1 October 1986. The plan of attack consisted of five phases, which are summarized below:

1. Determine the role of ASTA in the larger context of the total ATC system.

2. Identify the functions to be carried out and the required surface surveillance sensor accuracy.

3. Conduct a cost-benefit analysis of each function identified to determine those functions for which automation would provide the most benefit for the investment.

4. Develop a modular design for the automation of airport surface traffic control and evaluate the potential performance of that design.

5. Prepare a specification for a simulation of the proposed ASTA system. This simulation would be the next step in the overall development of an operational system.

The organization of this report follows these five phases.

2. ASTA & ATC SYSTEM INTERACTION

This chapter is a short review of the way that airport tower cab controllers interact with other elements of the ATC system. An understanding of the current manual system is required since the same functions will be carried out under automation even though the interfaces between different elements of the system may change.

2.1 Description of Current Tower Control

Several controllers are present in the tower cab. The one responsible for traffic on the active runway is called the local controller. He is responsible for take-offs, landings and all airborne local* traffic. The person responsible for all ground traffic not on the active runway is called the ground controller. The pilot of a departing aircraft makes his first radio contact with the tower by calling the clearance delivery controller. The clearance delivery controller reads the enroute clearance which has been forwarded from the center for the departing aircraft, and assigns an engine start time. The next radio call from the pilot would normally be to the ground controller when the aircraft is ready to taxi for take-off. The ground controller is responsible for the aircraft until it arrives at the active runway. At that point the pilot contacts the local controller for take-off clearance.

The process of passing the responsibility for an aircraft from one controller to another is called a "hand-off." Prior to executing the hand-off the controller giving up responsibility must "coordinate" with the controller accepting responsibility. After the new controller has accepted the hand-off, the pilot is instructed to change his radio to the frequency monitored by the new controller. In the tower cab hand-offs are coordinated easily, because the controllers involved are standing next to one another. After take-off, the local controller must hand-off the aircraft to a departure controller in another location. Consequently, coordination for that hand-off is done over a phone link. When the ground controller has to taxi an aircraft across an active runway he typically will coordinate with the local controller, but not initiate a hand-off. Arriving aircraft are normally handed off to the local controller from the approach controller near the outer marker after coordination.

When the airport is idle, aircraft can initiate taxi, take-off, or landing whenever they are ready. When there is heavy demand for runway use, several forms of flow control are initiated to meter traffic in a way that will make maximum use of available capacity. The first task is to predict the capacity of the airport or saturated element of the system and communicate the prediction to the flow control authority. National flow control regulates

*The term "local" usually signifies traffic within about 5 nmi of the airport.

departure times in an attempt to match the capacity predicted for saturated terminals. The enroute center exercises departure flow management to prevent saturation of sectors handling departures. The center also exercises enroute metering so that the arriving aircraft flow to an airport will be matched to the landing capacity and not overload approach control. Communication and negotiation are required between the tower controllers and the flow control authorities.

2.2 Description of Airport Surface Control Areas

An active runway is defined as one currently in use. When multiple runways are used, they are all considered active runways. The local controller is responsible for the clearance of all movements over an active runway. At the present time, surveillance of the active runway is accomplished visually or with the assistance of Airport Surface Detection Equipment (ASDE) radar. Communication is by means of VHF radio on the channel designated for tower control. All aircraft using the active runway are required to receive clearances and monitor the tower frequency. Light signals are used in the event of radio communications failure and for authorized vehicles that are not radio equipped. The active runway should have the highest priority for surveillance and communications coverage.

Taxiways are the designated paths by which aircraft proceed from the runway to other positions on the airport. The ground controller is responsible for approving all movements along the taxiways. He is usually stationed in the tower cab next to the local controller and has access to the same surveillance information. He is assigned a separate VHF communications channel for the purpose of talking to aircraft. The ground controller also has a second radio channel for the control of ground vehicles such as fuel trucks, emergency equipment, service vehicles, etc. He also can use the available light signals. Approval must be obtained for all movements on the taxiways by aircraft or vehicles whenever the control tower is in operation. Helicopters using hover taxi (under 20 kts) or air taxi (over 20 kts) often follow the taxiways while airborne at low altitude (under 100 ft.). Taxiways have high priority for surveillance and communications coverage, second only to the active runway.

The ramp or apron is a defined area on an airport intended to accommodate aircraft for purposes of loading or unloading, refueling, parking or maintenance. In general, approval must be obtained from the ground controller prior to moving an aircraft or vehicle onto the movement area. The movement area is that portion of the airport surface in which ATC exercises control. The movement area is established by the tower chief and is normally described in local bulletins issued by the control tower or airport manager. At major airports the boundary of the movement area is typically between the gate and the ramp; i.e., clearance is requested for "push-back" from the gate by a tractor, to be followed by a clearance to taxi. Establishment of the movement area is influenced by the surveillance coverage available. Ramp areas that can be seen visually from the tower are normally included in the movement area.

The presence of large numbers of ground vehicles on a ramp can make it difficult or impossible to exercise central control over all vehicles. When the vehicle density becomes very high, the ramp may be designated to be outside the movement area. The surface surveillance requirement at an airport depends therefore upon whether or not the ramp is designated to be within the movement area. Ramp areas are obviously of lower priority than runways and taxiways for surveillance.

The gate area is where the aircraft park for passenger boarding through movable walkways. At larger airports the aircraft enter the gate nose first and have to be pushed back out of the gate area onto the ramp where forward motion is unobstructed. Communication is necessary with aircraft in the gate area. However, surveillance is relatively unimportant since the gate is normally outside the movement area. In current operations, initial radio contact is established while parked at the gate with a call to clearance delivery prior to engine start. In the event of gate holding due to departure delays, clearance delivery will assign the engine start time. Clearance delivery will also read the flight clearance including the assigned transponder code. No surveillance or control over the movement of traffic is exercised by clearance delivery. After receiving and acknowledging the clearance, the pilot contacts ground control for approval to push back and taxi. At smaller airports, the clearance delivery function may be handled by the ground controller. It should be clear that communications are desirable while in the gate area. However, precision surveillance is not necessary, other than to determine at which gate the aircraft is located.

2.3 Scope of Surface Automation

The control of airport surface traffic today can be described as manual. Surveillance is predominantly visual with occasional help from an ASDE radar when visibility is poor. Sequencing, spacing, routing, and monitoring are done mentally by the human controller. Communication is by voice over VHF radio. Guidance of individual aircraft is achieved entirely through the pilot's visual perception. In the ASTA system the ground controller would still remain in the loop with legal responsibility for the clearance of aircraft and vehicles.

The controller is kept in the loop to allow him to take over in the event of a failure of the automated system. He would be unable to regain control without having been involved throughout the process. Consequently, automation refers not to a mechanization of the total process, but to computer assistance in the many separate tasks performed by the human controller, who remains in command. Many of these tasks can be classified as monitoring and record keeping. Some of them involve decision making, but most automated decisions would be presented to the human controller for approval. As an example, one major decision is the selection of a runway configuration. The configuration is the combination of active runways used for landings and

departures. The configuration determines the capacity of the airport. The choice of configuration and the timing of the reconfiguration depend upon a large number of factors such as the weather, wind, traffic demand, equipage, maintenance status, noise abatement, manpower available, time of day, day of year, etc.* Although the logic that develops configuration recommendation may be very complex, the final decision will still rest with the controller team.

Runway configuration has a major impact on the rest of the ATC system [1] and requires coordination with TRACON planners, enroute planners, and national flow controllers. National flow control needs to know the predicted capacity in order to meter the traffic departing other airports. Enroute controllers further meter the flow into the terminal, and terminal controllers must channel the traffic to the designated runways. Runway re-configuration must be timed properly to get from one configuration to another without wasting runway capacity. Automation can help in the decision process by making recommendations, and by assisting in communication, coordination, negotiation and prediction. The final decisions, however, remain with the human controllers.

In summary, there are necessary interfaces between the surface automation and controllers in the center, approach control, departure control, and central flow control. The interactions involve hand-offs, coordination, negotiation, and information reporting.

* Automation to assist in making this decision is being developed under the Runway Configuration Management System (RCMS) program.

3. FUNCTIONAL DESCRIPTION OF SURFACE TRAFFIC CONTROL

In this chapter the functions that need to be carried out by the surface automation will be described. Specifications on coverage, accuracy, and update rate will be discussed.

3.1 Necessary Functions

The necessary functions of the Airport Surface Traffic Automation System include the following:

Surveillance of surface traffic
Communication between automation and traffic
Conflict detection
Collision alerting and avoidance
Equipment monitoring
Operations recording
Strategic planning of airport configuration
Tactical management of runway usage
Coordinated taxi clearance
Conformance monitoring

3.2 Surveillance Possibilities

There are several ways in which surveillance data can be obtained for an airport surface traffic automation system. The most probable techniques are listed below with comments about each.

3.2.1 ASDE Radar

The ASDE radar provides good accuracy and update rate. The specification for ASDE-3 [2] indicates resolution of 40 ft in range and 80 ft in azimuth at a range of 3600 ft with an update rate of once per second. The specification for radar accuracy is 12 ft, one sigma, relative to ground truth. The principal shortcoming of the ASDE radar is that it does not provide identity or altitude. Without a means of positively identifying radar targets, it is not possible to base surface automation on ASDE surveillance alone.

3.2.2 Mode S Terminal Sensor

The Mode S sensor provides both identity and altitude. It also has fair accuracy (range bias = ± 125 ft, range repeatability = 40 ft, bearing standard deviation = 0.04°), but the scan rate of a rotating beam sensor (4 sec) is slow. The Mode S sensor also has data link capability, but with a message delivery delay of up to one scan period. The scan rate can be improved by a factor of two by using back-to-back antennas. The major shortcoming of any rotating beam Mode S sensor for surface surveillance is the positional error caused by the ± 125 ft range bias in the transponder.

3.2.3 Mode S Surface Multilateration System

The Mode S range bias problem can be overcome by using a system of omni-directional Mode S receivers to provide aircraft location by time difference multilateration. Accurate position is obtained by measuring the time difference between arrival of the signal at the multilateration receivers. This eliminates the error due to transponder turn-around-time bias. The maximum time difference is the maximum distance between receivers divided by the propagation speed (e.g., 25,000 ft max. separation distance means 25 μsec max. time difference). Accuracy is determined by the accuracy of the timing plus the hyperbolic geometry. A minimum of three non-colinear receivers are necessary for a two dimensional fix.

The primary use of an airport Mode S multilateration system would be to provide the information for an unambiguous identity tag on each aircraft. The Mode S multilateration system could also provide coverage of ASDE blind spots caused by ground clutter, heavy precipitation, or other line-of-sight restrictions. An increased interrogation rate would make it possible to determine velocity more accurately. Mode S surveillance also provides data link communication as a by-product.

A 1975 study by O'Grady, Maroney and Hagerott of TSC established a resolution requirement of 150 ft to correlate ASDE targets and an accuracy of 25 ft, one sigma [3] for the multilateration system. A 1979 TSC study [4] estimated an accuracy requirement of 16 ft, one sigma. This accuracy is achievable with a Mode S multilateration system.

3.2.3.1 Multilateration on Mode S Squitter

Mode S multilateration can be achieved without requiring additional Mode S interrogation or replies. Each Mode S aircraft spontaneously transmits a reply (termed a squitter) once per second. The squitter includes identity but no altitude.

3.2.3.2 Multilateration on Mode S Interrogation Response

Interrogation by the ground system can cause aircraft transmissions at rates faster than once per second. The replies can contain both identity and altitude. Position can be obtained in the same manner as above. If round-trip times are measured, the position can be determined with two receivers, but with an error due to the transponder turn-around-time bias. With three round-trip times the bias can be estimated. The interrogations and replies can also be used to carry Mode S data link messages. However, the effective radiated power is lower than a rotating beam antenna, because the omni-directional antennas have less gain.

3.2.3.3 Transponder Monitoring

The future ATC system will rely to a greater extent on a properly functioning transponder and altitude encoder. The airport surface system should monitor the performance of these devices prior to take-off clearance and alert both pilot and controller of any malfunction before the aircraft enters the ATC system. An aircraft arriving at the airport with malfunctioning transponder or encoder should be warned prior to shut-down so that repair can be initiated.

Any error in the turn-around time of the transponder leads to a Mode S sensor range error. The multilateration system would provide a measurement of the turn-around error. The Mode S terminal sensor cannot determine the error without additional information [5].

3.2.4 Operations Monitoring and Recording

The effectiveness of an airport is measured by its capacity. A number of measures of operations are useful for the monitoring, recording, and prediction of airport capacity. These include take-off and touchdown position and time, inter-arrival spacing, runway occupancy time after landing, number of aircraft undergoing delay, etc. These data are useful in real time for improved control. Automatic recording of the data relieves the controller of the task of logging each operation.

The goal for achieving optimum runway utilization is to deliver aircraft to the runway threshold with a one-sigma error of under 5 seconds [6]. For monitoring performance it would be adequate to measure aircraft locations every second.

3.3 Conflict Alert at Runway and Taxiway Intersections

This function would provide a warning to both pilot and controller whenever potential conflicts exist at intersections. Only one aircraft should be on the active runway during a take-off or landing. When a take-off or landing is in process, the system would issue a warning to all other aircraft in the vicinity of the runway and advise the controller that the warnings were issued. Similar warnings would be issued when two aircraft approach a taxiway intersection simultaneously, or if two aircraft approach too closely in an overtake situation.

The important parameter for predicting conflicts is the speed of the taxiing aircraft. Aircraft taxi speed is around 20 knots and an accuracy of a few knots is desired. This is about the same accuracy as a car's speedometer or an aircraft inertial navigation system. The velocity accuracy, σ_v, of a steady-state filter is given by [7]

$$\sigma_v = \frac{\sigma_a T}{\sqrt{2}} \sqrt[4]{1 + \frac{8\sigma_r}{\sigma_a T^2}} \tag{1}$$

where σ_a = acceleration uncertainty

σ_r = position error

T = sample period.

It can be seen that the velocity accuracy depends more strongly on the sample rate than it does on the position accuracy. Assuming $\sigma_a = 0.1g$, $\sigma_r = 25$ ft., T = 1 sec, $\sigma_v = 3.8$ kts. If greater accuracy were needed after detecting a conflict, sampling could take place at a faster rate until the conflict was resolved.

3.4 Improving Capacity

The purpose of several of the functions necessary for surface traffic automation is to increase the capacity of the airport, i.e., the number of operations per unit time. Because of the importance of improved capacity, an FAA-sponsored program is already underway to carry out the strategic planning of airport configuration cited in Section 3.1. Although this program is important to the overall efficiency of the airport surface operation it is not considered to be part of the ASTA program, because it already exists as a program in its own right. However, there is an ASTA function that interacts closely with this program. This function is identified in the following paragraphs along with a description of the runway configuration management program.

3.4.1 Runway Configuration

The prediction of airport capacity is strongly coupled to the runway configuration selected. The Runway Configuration Management System (RCMS) will be a strategic planning program which recommends a particular configuration given the existing conditions and constraints. Work on this system is underway. The system will recommend changes in runway configuration and the times for their execution, but will not provide tactical advice as to which aircraft will actually use which runways. Such a tactical planner is also needed.

3.4.2 Tactical Runway Planning

For landings, the responsibility for assigning individual aircraft to runways rests with approach control. For departures the responsibility for runway assignment remains with the tower. Departure flow management is a program already underway intended to schedule the time of departure for individual aircraft [8]. A tactical planner to generate taxi clearances for departure would need to satisfy both time constraints imposed by departure flow management and runway constraints imposed by landing traffic. Within those constraints there should still be freedom to optimize for maximum utilization of the runway. Such a tactical planner is considered part of the ASTA program and would have to interface with approach control and departure flow management.

Here the ground controller would stay in the loop to exercise final approval authority, probably designating origin or destination on the airport. The automation would suggest actions that the controller would monitor and modify or approve. Once approved, the taxi instructions would be sent to the pilot automatically via the Mode S data link. It is possible that the system could also activate taxiway centerline lights and other signaling devices to assist pilots in following the taxi instructions. Software for this type of automation would be airport specific. The accuracy necessary to monitor aircraft would be similar to that required for conflict alert.

3.5 Automatic Clearance Delivery

At major terminals one controller and one voice channel are dedicated solely to the delivery of the flight clearance. The clearance consists of detailed instructions for the climb-out and enroute portion of the flight. In the event of gate-hold procedures, the clearance delivery controller also issues the engine start time. The clearance delivery controller presently reads the clearance over the voice channel from a printer or video display. It could go directly to the cockpit using data link.

4. COST BENEFIT ANALYSIS

The purpose of this chapter is to establish the costs and benefits associated with the functions that constitute an automated airport surface control system.

4.1 The Objectives of ASTA

In order to establish the costs and benefits of each function that would be carried out by the automated airport surface control system, it is necessary to define the objectives of the surface automation program. The following set of objectives are listed in order of importance:

1. Maintain the safety of surface operations at or better than current levels while accomplishing the other objectives of automation.

2. Increase the capacity of the airport by operating in a manner and configuration that will produce maximum throughput.

3. Improve schedule reliability by delivering aircraft to the runway properly ordered at their desired departure times, and expeditiously to their gate after landing.

4. Improve controller efficiency under the increased demands of greater traffic and lower visibility.

5. Provide the necessary improvements to support other FAA programs aimed at increases in overall system capacity and reduction in Air Traffic Control delay.

4.2 Safety Benefits

4.2.1 Economic Considerations

Achievement of the objectives cited above would bring about benefits associated primarily with safety, increased throughput, and reduced delay. It is normal to attempt to express these benefits in common units, typically dollars, in order to compare them first with one another and ultimately with the necessary costs to bring them about. The dollar value of safety is difficult to quantify. However, a rough measure can be obtained by associating a dollar value with the loss of life and property that accompany an aircraft accident. The replacement cost of an airliner varies from about $25M for a small aircraft the size of a Boeing 737 up to about $100M for a large, wide-body the size of a Boeing 747. The loss of a single life is estimated at about $0.5M. Using 1986 traffic data and dividing the total number of passengers by the total number of flights, the average is 67 passengers per flight. From this number it can be seen that the dollar value of preventing the 100% fatal crash of a single aircraft is a benefit that on average could exceed $80M.

4.2.2 Public Safety Considerations

Looking only at the economic aspect of safety does not provide a complete assessment of the potential benefits. The federal government is charged with the responsibility for regulation of public transportation in a way that makes it safe. The public perception of air safety outweighs the economic losses to aviation accidents when evaluating the government's performance. The public is very sensitive to loss of life due to accidents in public air transportation, more so than private air transportation and much more than private automobile. For this reason the potential benefit of avoiding a fatal accident is far more valuable than the cost of the loss.

4.2.3 Prior Accident History

Looking at the history of accidents on the airport surface in the United States [9] over a 19-year period (1962-1980) there are an average of about 11 accidents annually resulting in about one fatality and one serious injury per year. The fatalities and serious injuries were however, associated with only a very few of the accidents. The December 1972 accident at Chicago O'Hare alone accounted for 10 fatalities out of the total. While historically the safety record has been good, the potential for serious accidents on the airport surface increases with increased operations under low visibility. The 1977 Tenerife accident in reduced visibility on an airport surface outside the U.S. killed 583 people and destroyed two wide-body aircraft. Using the figures above, the cost of a similar accident in the U.S. today would be over $490M, and would certainly lead to a public demand for safety improvements.

4.2.4 Recent Accident History

A study of more recent data confirms the previous finding, i.e., the accident history remains good, however, increased incidents of runway incursions have emphasized the potential for disaster. The number of runway incursions rose from 77 in 1984 to 102 in 1985 and 115 in 1986. A special investigation of 26 selected incidents of runway incursion was reported by the NTSB in May 1986 [10]. The investigation was triggered by the near collision of two Northwest Airlines DC-10 aircraft on March 31, 1985 at the Minneapolis-St. Paul International Airport. One DC-10 overflew the other with a reported clearance of under 75 feet. There were a total of 501 persons aboard the two aircraft. The frequency and potential severity of these incidents make it imperative that steps be taken to reduce the probability of their occurrence. The NTSB study cited 24 conclusions, most of which focussed on controller and pilot errors. The reasons for these errors included the failure of controllers to sight a potential conflict, a breakdown in communication procedures between pilots and controllers, a failure in coordination between controllers, controller loss of short-term memory, pilot disorientation, and preoccupation of both pilots and controllers. The primary NTSB recommendations were for operational changes, better training, better airport signs and markings, and redundancy of supervisors in the tower cab.

4.2.5 Surface Automation Safety Functions

It would appear that surface automation could also help reduce these errors with three major functions, namely:

1) Improved surveillance and communications,
2) Traffic displays in the cockpit and the tower,
3) Conflict alerts to both controllers and pilots.

4.3 System Issues in Evaluating Delay and Throughput Benefits

4.3.1 Overview

The potential for surface automation to reduce delay is also difficult to quantify. One reason is that the cause of the delay is not necessarily due to congestion where the delay is occurring. Currently, when flow control is in effect aircraft are delayed on the ground before they start their engines. But the cause of the delay is due to excess demand on the runway at their point of intended landing. In order to determine the extent to which surface automation can reduce delay, it is necessary to understand the interaction of the airport surface with the total process by which delay is created. Any surface automation function that can increase airport throughput has the potential to eliminate the high cost of delay. However, many of the automation functions will increase throughput only indirectly. An example of this is the delivery of aircraft to the runway for take-off at desired times. It can be an important function for the prevention of delay if the desired take-off times have been properly selected by departure flow management. Consequently, the delay improvement results from the combined effect of properly selecting the departure times and insuring the timely delivery of the aircraft to the runway. Either function by itself would not improve delay without proper execution of the other function. Several of the surface automation functions have this property.

4.3.2 Delay vs. Throughput

The reduction of delay and the increase of throughput are prime goals. However, because of the nature of traffic control systems, a careful trade-off must be engineered in pursuing these two goals. Figure 4.1 depicts in general terms the behavior of the airport. As a given system configuration is operated at increased throughput, the delays that are suffered increase. The rate of increase in delay increases as demand reaches the ultimate capacity. The locus of delay-throughput points at which the system can be operated with a given configuration is called the operating curve for that configuration. When the configuration is improved through automation, a new operating curve is established. The improved configuration allows a choice of a new operating point that will result in reduced delay, increased throughput, or some combination of the two.

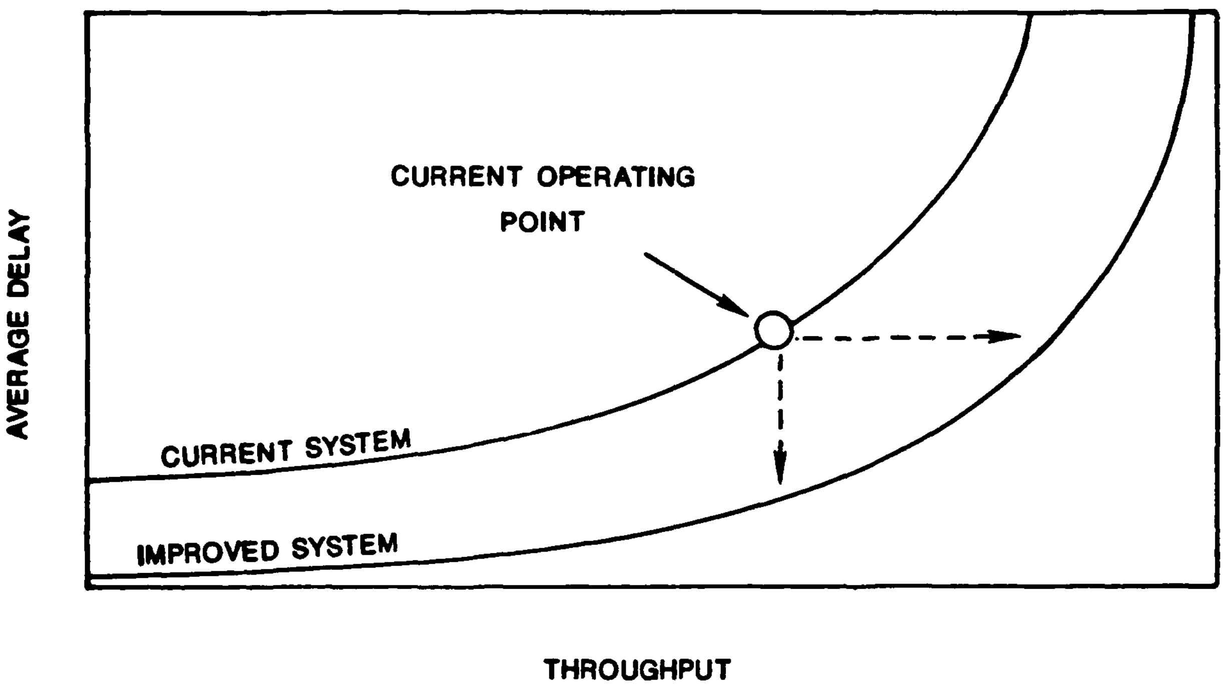

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Fig. 4.1. Delay vs. throughput.

4.3.3 Current Operating Point

A rough idea of the operating point of the total current ATC system can be obtained from inspection of official data on airline operations. In 1986 the national ATC system experienced an average of 8 minutes delay per flight with a throughput of 6.2 million flights per year. Comparing these figures with those from the previous year reveals that between 1985 and 1986 there was a 25% increase in delay compared with an 8.5% increase in the throughput. This provides a crude implication that the system is operating at a point where a 3% increase in delay occurs for each 1% increase in throughput.

4.4 Delay and Throughput Benefits

4.4.1 Delay Costs

The estimated cost of delay [11] to the airlines in 1986 was $1200M. Dividing that cost by the total delay gives $1400 as the average cost to an airline per hour of delay. The value of an average airline passenger's time is currently considered to be $18 per hour. Using the average number of passengers per flight, the value of the lost time to the passengers of an average flight is $1200 per hour of delay. The average total cost of an hour of delay is therefore estimated at $2600 per aircraft. Using the figures for 1986 the total cost of delay was over $2 billion. The total potential benefit of eliminating the delay is very large. Increasing demand will increase this number dramatically by the time surface automation can become operational.

4.4.2 Value of Increased Throughput

The value of increased throughput is again difficult to quantify. It might be argued that the value of the flight that caused the most recent increase in the throughput must be at least equal to the cost of the current delay, or there would have been no economic incentive for adding the additional flight.

As the operating point of the system moves toward higher delays, the marginal benefits of automation improvement increase, regardless of whether the improvement is realized in terms of decreased delay or increased throughput. It must be kept in mind that the value of increased throughput can diminish sharply if the demand for service weakens at the higher throughput level. However it appears that for the foreseeable future there will be sufficient growth in air traffic demand to take advantage of the improvements that are likely to result from ATC automation.

4.4.3 Summary of Automation Benefits

In summary, an automation system that could eliminate all the current measured delay would provide economic benefits in excess of two billion dollars. With sufficient demand, the value of the improved system increases at a rate that is at least three times the rate at which the demand increases. For realization of this benefit, several aspects of surface automation must participate; however, it cannot be accomplished by surface automation alone.

4.5 Schedule Reliability Benefits

4.5.1 Definition and Significance

Schedule reliability is defined to be the probability that a flight will arrive at the gate within a specified time (typically 15 minutes) of its scheduled arrival time. If overall delays are reduced, then schedule reliability should naturally improve.

An important consequence of increased schedule reliability is the reduction in the number of missed connections. A passenger who must make a connecting flight may be insensitive to the length of the delay on the first flight so long as the passenger (and that passenger's luggage) are successful in making the connecting flight. A wait of several hours or even overnight due to a missed connection is much more costly to the passenger than the delay costs associated with the first flight. Such costs do not appear in the official delay tabulations made by the FAA.

4.5.2 Schedule Reliability Costs

Schedule reliability problems are costly to the airlines since they require additional bookings, schedule changes, equipment and crew reroutings, etc. They also discourage the use of connecting route structures that would best serve the public and make the most efficient (hence profitable) use of airline investments. Other benefits of improved schedule reliability are increased passenger confidence in air travel, reduced delay associated with waiting for an open gate, reduced congestion of the airport surface, and reduced baggage-handling costs.

From the foregoing comments, it is clear that the dollar benefits of increased schedule reliability are substantial, but difficult to calculate.

4.6 Controller Workload Benefits

Controller workload in the ATC system has long been recognized as both a personnel problem and a potential safety problem. It is also an efficiency problem since high workload levels often force the controller to employ workload-efficient techniques rather than traffic-efficient techniques.

Among the benefits of workload reduction are:

- Increased career potential for control personnel. It is recognized that some controller skills tend to degrade with age. Automation should alter workload so that those skills that improve with age become increasingly important, and those skills that degrade with age are largely handled by automation.

- Increased safety. High workload increases the likelihood of simultaneous problems creating a distraction that leads to a controller error. Automation should improve safety in two ways: by providing back-up safety aids such as conflict alert, and by reducing workload peaks that increase the likelihood of controller error.

4.7 Relating Functions to Benefits

4.7.1 Surface Surveillance and Communications

All of the automation benefits depend upon surveillance and communications. These functions should receive the highest priority, since none of the benefits can be achieved without them. Surveillance, identification, and data link for airborne aircraft will be provided by the ASR-9/Mode S sensors augmented, in some instances, by a parallel approach monitor [12,13]. A new surface surveillance and communication system must be developed to provide surveillance, identification, and data link for surface aircraft and to provide surveillance and classification of surface vehicles. Surface surveillance and communication can provide direct safety and throughput increases as well as indirect support of other improvements. Once the location and identity of the aircraft are part of the data base and a data link is provided, the other functions can proceed.

4.7.2 Conflict Alert and Collision Avoidance

The next highest priority should be given to the conflict alert function. This should be applied to runway incursions, runway intersections, approach monitoring, and taxiway intersections. This should help prevent airborne and ground collisions. As the throughput of the airport is increased, the inter-aircraft separations are decreased and the potential for collision is higher. By improving safety protection before taking steps to increase the capacity, the probability of a collision accident is reduced.

4.7.3 Maximum Runway Utilization

Once the protection against collision has been enhanced, emphasis can be placed on those functions that will give the highest payoff in terms of increased throughput and reduced delay. High priority should be given to those automation aids that assist in obtaining maximum utilization of the runway. These include automation to predict, monitor, and record data on the runway operation such as aircraft touchdown time, runway occupancy, intersection crossing, take-off roll, etc. Predictions aid the controller in making timely tactical decisions. Monitoring is an aid to flow control and planning. Recorded data allow the analyst to identify problems and recommend improvements. Included in these functions is the planning aid which recommends airport configurations based on maximum capacity for the given and

forecast status of the weather, wind, maintenance plan, facilities, etc. These functions have a direct benefit in terms of improved throughput and reduced delay. The potential payoff is high, but it cannot be achieved without the surveillance improvements and the safety guarantee that reduces the risk of collision. Also included in this grouping are those functions that support improvements in the total ATC system, such as departure flow management.

4.7.4 Automated Clearances

Further increases in throughput and improved safety are made possible by those functions that will reduce the controller workload. These include automatic taxi instructions, automatic clearance delivery, transponder and encoder checks, etc. While the benefits from these functions are very real, the benefits-to-cost ratio is probably less than for the functions discussed above. Furthermore, the technology needed for these functions will probably be applied first in the enroute and approach control areas before it is adapted to the airport surface, because the benefits payoff is greater there than on the airport surface.

4.8 Summary

In summary, the potential benefits of airport surface automation are large. However, the benefits associated with delay reduction can only be achieved with the aid of other programs providing automation improvements to other interacting parts of the ATC system. Those programs in turn require surface automation improvements for their success. The priority to be given to the various functions is as follows:

1. Surface Surveillance and Communication
2. Conflict Alert and Collision Avoidance
3. Maximum Runway Utilization
4. Automated Clearances.

5. DESIGN OF THE ASTA SYSTEM

In this chapter the design of the proposed system for surface automation will be outlined. Because the system will need to operate at airports of various sizes and shapes with differing constraints, an overview will be made of the candidate airports. The modular elements of the system will be defined to accomplish the functions that have been identified.

5.1 Comparison of Individual Airports

5.1.1 Airports Analyzed

In order to see a cross section of the candidate airports, diagrams were obtained for the top 25, FAA-operated air carrier airport traffic control towers as listed in the FAA Statistical Handbook of Aviation for Calendar Year 1984. This was the most current listing when the airport sample was selected for the study. More recent data can change the ranking of airports but should not affect the conclusions of the study. Table 5.1 shows the rank order of air carrier operations and also lists the rank for total operations. Airports that do not have air carrier activity are not of primary interest for this study despite the fact that they show large operation counts. An operation is defined as an arrival at or departure from the airport. General aviation airports generate large counts, because their traffic consists of small aircraft operation predominately VFR with frequent takeoffs and landings. Among the selected top 25, there is a considerable difference in the total number of operations and traffic mix. The airport diagrams for these 25 are shown in Appendix A. It can be seen that there is also considerable variation in geometric size and shape.

5.1.2 Comparative Statistics

Using these airport diagrams, comparative statistics were obtained as shown in Table 5.2.

5.1.2.1 Airport Physical Size

In the first column the airport physical size was quantified by the radius of the smallest circle which could circumscribe all designated runways and taxiways. The physically large airports like Dallas and Denver have a radius three times larger than that of Washington National.

5.1.2.2 Number of Runway Surfaces

In the second column the number of runway surfaces are tabulated. Each runway surface can have two landing directions. Chicago and Dallas each have seven runway surfaces while Phoenix and Seattle have only two.

TABLE 5.1

TOP 25 FAA-OPERATED AIRPORT TRAFFIC CONTROL TOWERS, BY RANK ORDER OF AIR CARRIER OPERATIONS AND BY AVIATION CATEGORY INCLUDING TOTAL OPERATIONS RANK
CALENDAR YEAR 1984

Tower	Air Carrier Rank	Air Carrier	Air Taxi	General Aviation	Military	Total Operations Rank	Total Operations
Chicago O'Hare International	1	625,033	66,766	45,540	3,957	1	741,296
Atlanta International	2	547,112	101,051	39,747	1,572	2	689,482
Dallas Ft. Worth Regional	3	409,278	91,784	22,720	782	5	524,564
Denver Stapleton Int'l	4	348,649	94,541	68,036	1,294	6	512,520
Los Angeles Int'l	5	329,475	147,356	69,008	4,917	4	550,756
San Francisco	6	273,157	75,317	52,626	2,750	9	403,850
St. Louis Int'l	7	260,583	71,791	55,263	8,269	11	395,906
Newark	8	254,399	74,370	40,564	657	16	369,990
La Guardia	9	246,739	81,634	36,269	476	17	365,118
Miami International	10	217,127	61,262	73,623	573	22	352,585
Pittsburgh Greater Int'l	11	211,036	94,927	41,815	7,854	21	355,632
John F. Kennedy Int'l	12	210,341	117,114	28,513	679	20	356,647
Boston Logan	13	207,203	132,223	47,754	242	12	387,422
Minneapolis St. Paul Int'l	14	205,575	45,042	79,500	7,721	26	337,838
Phoenix Sky Harbor Int'l	15	196,239	56,109	138,964	7,986	10	399,298
Detroit Metro Wayne Co	16	195,156	65,364	65,373	376	29	326,269
Washington National	17	191,479	63,533	85,253	417	25	340,682
Houston Intercontinental	18	188,712	79,460	59,257	953	27	328,382
Charlotte Douglas	19	154,753	61,801	89,972	3,855	31	310,381
Honolulu	20	154,121	75,442	82,943	31,291	24	343,797
Cleveland Hopkins Int'l	21	145,995	23,306	70,000	1,726	51	241,027
Philadelphia Int'l	22	144,028	124,585	74,694	1,402	23	344,709
Seattle Tacoma Int'l	23	142,717	59,824	21,297	420	60	224,258
Memphis International	24	128,509	53,603	112,655	4,280	34	299,047
Cincinnati Greater	25	128,482	495	38,756	360	110	168,093

NOTE: Total Operations rank was based on total air traffic activity at 395 FAA-Operated Towers.

Air Carrier operations rank was based on air carrier activity at 306 FAA-Operated Towers.
Not all FAA-Operated Towers handle air carrier operations.

TABLE 5.2

COMPARATIVE STATISTICS FOR TOP 25 AIRPORTS

Airport	Radius (nmi)	Runway Surfaces	Parallel Surfaces	Runway Intersections	Cat. I Approaches	Cat. II Approaches
Chicago	1.6	7	2+2+2	7	11	2
Atlanta	1.2	4	4	0	7	2
Dallas	2.2	7	4+2	0	7	1
Denver	2.1	6	3+3	0	5	1
Los Angeles	1.5	4	4	0	8	1
San Francisco	1.2	4	2+2	4	3	1
St. Louis	1.1	5	3	2	3	0
Newark	1.0	3	2	0	3	1
La Guardia	0.8	3	2	2	3	0
Miami	1.6	3	2	1	5	0
Pittsburgh	1.7	4	3	2	5	1
Kennedy	1.7	5	3+2	2	7	2
Boston	1.1	5	2+2	6	5	1
Minneapolis	1.1	3	2	2	5	1
Phoenix	1.1	2	2	0	1	0
Detroit	1.4	4	3	3	5	2
National	0.6	3	0	3	1	1
Houston	1.2	3	2	0	4	1
Charlotte	0.9	3	2	1	3	0
Honolulu	1.5	4	2+2	2	2	0
Cleveland	0.9	5	2+2	7	3	1
Philadelphia	1.3	3	2	1	4	1
Seattle	1.0	2	2	0	2	1
Memphis	1.5	5	2	1	6	1
Cincinnati	0.8	3	2	2	4	1

5.1.2.3 Number of Parallel Runways

The third column indicates the number of parallel runway surfaces. When there is more than one set, they are separated by a plus sign. Atlanta, Dallas, and Los Angeles have quadruple parallel runways. Only Washington National is among the top 25 with no parallel runways.

5.1.2.4 Number of Runway Intersections

The fourth column shows the number of runway intersections. The values go from zero to seven with 68% of the listed airports having at least one runway intersection. Data was also obtained on the instrument approaches available.

5.1.2.5 Number of Cat. I ILS Approaches

The fifth column indicates the number of ILS approaches to Category I minimums (200-foot ceiling and one half mile visibility). All 25 of the airports have Cat. I capability to at least one runway. Chicago has eleven Cat. I ILS approachs. Each runway surface has the potential for one ILS approach in each landing direction (although not simultaneously).

5.1.2.6 Number of Cat. II ILS Approaches

The sixth column indicates the number of ILS approaches to Cat. II minimums (100-foot ceiling and runway visual range of 1200 feet). Seventy-six percent of the group has Cat. II capability to at least one runway.

5.1.3 Other Comparisons

5.1.3.1 Cat. III Capability

In the selected group of 25 most active airports only New York's Kennedy airport has Cat. III capability (runway visual range of 700 feet).

5.1.3.2 Angled Runway Turnoffs

All of the airports have some angled runway turn-offs that are located to expedite exit from the runway. The average was 9.4 per airport. No attempt was made to quantify the exit speed capability. The criterion was an exit angle below 45° in a suitable location.

5.1.3.3 Number of Taxiways

Several metrics for counting taxiways were considered. Most airports have named taxiways where the names are a combination of letters, numbers, and historic identifiers such as inner, outer, parallel, scenic, etc. The typical number of named taxiways is about 45 with a high over 75. A named taxiway usually includes several continuous taxiway segments.

5.1.3.4 Number of Nodes

Define a node as any intersection of runways, taxiways or combination thereof. The number of nodes will be an important sizing parameter for automation of the airport surface and will depend strongly on the geometric size of the airport. Consider Dallas, Atlanta, Boston and Washington National as representatives of very large, large, medium and small airports in terms of relative physical dimension. The approximate number of nodes is shown in Table 5.3. (There is some choice in the selection of taxiway/taxiway intersection nodes.) It can be seen that there is also a large variation in size as determined by node count.

5.1.4 Definition of Airport Geometry

Define a path segment as the runway or taxiway segment joining adjacent nodes. A named taxiway or a runway surface can now be identified as an ordered set of path segments. The average number of path segments terminating at a node is about three. Since each path segment has a node at each end, the average number of path segments should be about three halves the total number of nodes. This structure forms a framework for defining the airport geometry for purposes of surface control. It has the advantage of flexibility in that nodes and segments can be added or deleted easily. Furthermore, an active runway is easily redesignated a taxiway or vice-versa as the consequence of an airport reconfiguration. The number of path segments for the airports of interest should be in the range of 50-250.

5.2 System Design

A modular design for automation of the airport surface was initiated. A number of the modules are described below. Work to date has established the functions to be carried out by ASTA and evaluated the benefits associated with each. The priority of the various functions according to their general classification was given earlier as follows:

1. Surface Surveillance and Communications
2. Conflict Alert and Collision Avoidance
3. Maximum Runway Utilization
4. Automated Clearances

The modules that have been identified are grouped under these same four classifications.

5.2.1 Surface Surveillance and Communication Modules

Four modules are defined under this functional grouping. The first is the sensor system which conducts the surveillance and provides data link communication. The second is the display system which provides the man-machine interface between ASTA and the controller. The third is a logic module for identifying and recording the events observed by the surveillance

TABLE 5.3

APPROXIMATE NODE COUNTS

Airport	Runway Intersections	Runway/taxiway Intersections	Taxiway/taxiway Intersections	Total Nodes
Dallas	0	62	94	156
Atlanta	0	37	76	113
Boston	6	28	30	64
Washington	3	18	15	36

sensors. The fourth is a transponder checker which monitors the integrity of the aircraft components that constitute the surveillance system. More detail is given in the listing below:

5.2.1.1 Surveillance and Communication Sensors

OBJECTIVE: Provide data base of position, altitude, and identity for all aircraft on or above the airport surface plus data link communications with equipped aircraft

DESCRIPTION: ASDE RADAR plus Mode S

INPUT: Data link messages for delivery to aircraft

OUTPUT: Aircraft identity, altitude, position, and track information to the Surface Traffic Display System plus data link messages

ISSUE: Interface between multilateration sensors for surface traffic and rotating beam sensor for airborne traffic

5.2.1.2 Surface Traffic Display System

OBJECTIVE: Provide interface between controller and ASTA System

DESCRIPTION: CRT, flat panel, or projection display system showing plan view of the airport surface with suitable control interface for designating targets, clearances, commands, etc.

INPUT: All information to be displayed plus controller inputs through voice or touch

OUTPUT: Visual display to controller plus controller commands to other ASTA modules

ISSUE: Type display and choice of input interface
How to indicate off-scale landing aircraft
Content of display (ID, velocity, orientation, etc.)

5.2.1.3 Operations Data Recorder

OBJECTIVE: Record operational data for performance analysis and continuing research and development on airport control and management

DESCRIPTION: Logic module for identification, classification, timing, and recording of events associated with the control of landing and departing traffic

INPUT: Surface surveillance data and aircraft identification data

OUTPUT: Runway throughput as function of traffic mix, time of day, configuration, etc.
Conflict Alerts
Taxi Conformance errors
Taxiway occupancy time
Runway occupancy time
Delay and causes
Interarrival spacing
Runway incursion count

ISSUE: Format for recorded data

5.2.1.4 Transponder and Encoder Checker

OBJECTIVE: To flag any transponder or encoder that exhibits abnormal behavior

DESCRIPTION: Logic to detect missing transponder replies, low reply rate, incorrect or invalid Mode C reply, improper Mode S data link transmissions, etc.

INPUT: Data from Surveillance and Communication Module

OUTPUT: Flag warning of malfunctioning transponder
Diagnostic message

ISSUE: Acceptable vs unacceptable performance levels

5.2.2 Conflict Alert and Collision Avoidance Modules

Three modules are defined under this functional grouping. The first is a runway incursion monitor which provides a warning to pilots and controllers when there is potential for a runway incursion. The second provides a warning to controllers when there is a non-aircraft intruder detected by radar on an active runway. The third is a taxi conformance monitor and conflict alert for airport taxiways. More detail is given in the listing below:

5.2.2.1 Runway Incursion Monitor

OBJECTIVE: Provide a warning alert to pilots and controllers whenever the potential for a runway incursion is present

DESCRIPTION: Logic module which is capable of detecting a potential or imminent runway incursion in time to provide warnings to pilot and controller

INPUT:	Surface surveillance data and aircraft clearances Runway incursion criteria
OUTPUT:	Pilot and controller warnings Estimates of touchdown, lift-off, and runway exit times
ISSUE:	Advanced Warning time Alert format False alarm rate

5.2.2.2 Non-aircraft Runway Intruder Detector

OBJECTIVE:	Provide a warning alert to controllers whenever a vehicle or other non-aircraft target is present on an active runway
DESCRIPTION:	Logic module which compares radar targets on the runway with known tracks of aircraft to detect non-aircraft targets plus warning system to alert controllers
INPUT:	Surface surveillance data, aircraft tracks, active runway identification
OUTPUT:	Displayed location and warning of non-aircraft runway intruders
ISSUE:	Alert format Controller override for authorized vehicles False alarm rate

5.2.2.3 Taxi Conformance Monitor and Conflict Alert

OBJECTIVE:	Provide a warning alert to pilots and controllers whenever an aircraft fails to conform to its taxi clearance or comes into potential conflict with another aircraft or obstruction
DESCRIPTION:	Logic module which is capable of detecting deviations from assigned taxi routings and potential conflicts between taxiing aircraft
INPUT:	Surface surveillance data and taxi clearances
OUTPUT:	Pilot and controller warnings
ISSUE:	Alert format False alarm rate

5.2.3 Maximum Runway Utilization

Three modules are defined which have the potential to improve runway utilization. The first is a strategic planner which recommends the best runway configuration under existing airport conditions. The second is a logic module to handle departure flow management. Such modules are already being developed in advance of the ASTA program, but should be considered part of an automated surface system. The third is a roll-out and turn-off guidance system which will be necessary to reduce runway occupancy time under severely reduced visibility in the event separation standards are to be further reduced below three miles. More detail is given in the listing below:

5.2.3.1 Runway Configuration Management System

OBJECTIVE: Select the runway configuration which will minimize total delay under constraints imposed by the weather, traffic mix, equipment status, maintenance operations, etc.

DESCRIPTION: Strategic planner to select optimum runway combination plus tactical planner to execute configuration changes

INPUT: Runway demand by category at least four hours in advance
Current and forecast weather data
Capacity predictions by runway configuration
Noise Abatement Plans
Manpower Shift Change
Conditional Runway Maintenance Plan
Equipment Status
Date and Time

OUTPUT: Recommended configuration plan and the associated capacity
Logic behind the recommendation

ISSUE: Already being developed in advance of ASTA program

5.2.3.2 Departure Flow Management

OBJECTIVE: Provide target take-off times for all departing aircraft

DESCRIPTION: Logic module which sequences departing aircraft in response to filed flight plans subject to departure separation criteria, wake turbulence minima, departure flow restrictions, noise abatement constraints, and central flow control planning.

INPUT: Data and negotiation capability with center, national flow control and departure sector controller

OUTPUT: Take-off sequence with target departure times

ISSUE: Already being developed in advance of ASTA program.

5.2.3.3 Runway Roll-out and Turn-off Guidance

OBJECTIVE: To provide guidance for roll-out and turn-off to achieve minimum runway occupancy under severely reduced visibility

DESCRIPTION: Surface surveillance, sensors, and cockpit displays to allow pilot to roll-out, decelerate, and exit the runway onto a high-speed turn-off with minimum runway occupancy time under Category III landing conditions (runway visual range below 700 feet). Sensors would probably include MLS, DME, and buried cable.

INPUT: Aircraft position relative to desired path

OUTPUT: Electrical signals suitable for guidance and control of aircraft steering and deceleration

ISSUE: Cost to benefit ratio
Runway occupancy time becomes important when aircraft spacing is reduced below 3 miles. However, that spacing may be difficult to achieve under Category III conditions. Also important with mixed departures and arrivals.

5.2.4 Automated Clearance Modules

Several clearances are received by aircraft on the airport surface. For departing aircraft, the first contact is with clearance delivery. This controller reads the pilot his enroute clearance and assigns an engine start time. After engine start, the next contact is with ground control who delivers the pilot his taxi clearance. Upon reaching the assigned runway, his next contact is with the tower local controller who provides the take-off clearance. For arriving aircraft, the tower local controller delivers landing clearance prior to arrival at the runway. Upon clearing the runway, the pilot contacts ground control who delivers the taxi clearance to the gate.

Three modules are defined to automate the process of delivering these clearances.

1. The first is a logic module which would generate taxi clearances automatically with minimal input from the ground controller. These taxi clearances would then be delivered by data link or computer generated voice. This module also has the potential to maximize runway utilization, because it supports departure flow management by providing timely delivery of aircraft to the runway for take-off.

2. The second module is a digitized billboard system which would support the taxi clearance with progressive instructions at intersections. The billboards would also permit the issuance of clearances or warnings to aircraft or vehicles without radio contact. In this context the billboard system also assists in preventing runway incursions. They could further be used for countdown to take-off with departures on intersecting runways.

3. The third module would automate the delivery of the enroute clearance. It has the potential to eliminate the need for a human controller at the clearance delivery position.

More detail is given in the listing below:

5.2.4.1 Surface Traffic Controller

OBJECTIVE: Provide for the safe and timely movement of traffic on the airport surface

DESCRIPTION: Logic module which determines content and timing of aircraft taxi clearances to support departure flow management and guarantee safe surface operations

INPUT: Surface surveillance data, controller inputs, data from departure flow management, pilot requests

OUTPUT: Taxi clearances

ISSUE: Controller-computer interface

5.2.4.2 Digitized Billboard System

OBJECTIVE: Provide alternative and back-up to voice and data link communications

DESCRIPTION: Display boards installed at runway exits and taxiway intersections capable of about 40 alpha-numeric characters for countdown to take-off on intersecting runways, alert warnings to prevent runway incursions, back-up communications in event of two-way radio failure or vehicles without radio, and progressive taxi instructions

INPUT: Automatic taxi clearance data
Aircraft location data
Controller message and location for display

OUTPUT: Display of appropriate message at proper time and location

ISSUE: Operational effectiveness

5.2.4.3 Clearance Delivery

OBJECTIVE: Communicate the enroute clearance and engine start time to an aircraft in response to its initial contact with the tower

DESCRIPTION: Logic module which receives clearances from the center or terminal control and transmits them to the appropriate aircraft upon request

INPUT: Enroute clearances from center and TRACON plus target take-off times from departure flow management

OUTPUT: Transmission of the appropriate clearance and engine start time to the proper aircraft upon request

ISSUE: Whether automation can eliminate the need for a human controller as clearance delivery

5.3 Description of Control Logic

5.3.1 Object-Oriented Programming

It is proposed that the control logic be developed using object-oriented programming. Objects are conceptual entities likened to real-world things such as runways, taxiways, aircraft, etc. They have properties that cause them to be distinguishable from other objects. Physical dimensions are an example of an object's properties. Objects can be made up of components which themselves are objects. For example, a taxiway consists of a number of connected path segments each of which is an object itself. Objects have an internal state which summarizes the status of the object. A path segment might have a status such as open, occupied, or closed. Objects have a set of operations that can be performed upon them according to rules that are established. For example, an aircraft may occupy a path segment if the path segment is open and the aircraft's weight does not exceed the weight limit of the path segment.

5.3.2 Airport Surface Representation

The objective is to represent the airport surface in terms of the structure described above. To this end, a list of objects are defined starting with a set of geographic points on the airport surface, which are called nodes. The node can be considered to be the intersection of any

taxiway or runway combination. However, additional nodes may be established anywhere on the surface where it is convenient. Reasons for establishing additional nodes might be to account for a bend in a taxiway or to identify the boundary for Cat. II holding. The nodes are the end points of the path segments where aircraft can taxi. A list of path segments would define a taxi route for the computer logic. The route would be specified to the pilot by a list of named taxiways which contains the assigned path segments. The airport would be displayed by showing the location (to scale) of all the nodes and path segments. Runways, taxiways, and taxi routes could be designated by color or shading. Object-oriented programming permits an easy transition between the representations of the airport surface used by the logic, the display, and the human operators.

5.3.3 Fundamental Objects

A listing of some of the fundamental objects is given below.

1. OBJECT: Node

   DEFINITION: Point on the surface of the airport which marks the end of a path segment

   PROPERTIES: Identification
   Geographic Location

2. OBJECT: Path Segment

   DEFINITION: Line between two nodes which describes the path which may be taken by an aircraft or vehicle in moving over the airport surface

   PROPERTIES: Identification
   Length
   Direction
   Weight limit
   Speed limit
   Terminal nodes (if not part of the identification)

3. OBJECT: Taxiway

   DEFINITION: Combination of path segments which make up the components of a named taxiway

   PROPERTIES: Name
   Component path segments

4. <u>OBJECT: Runway</u>

DEFINITION: Combination of path segments which constitute a runway

PROPERTIES: Identifying number
Component path segments

5. <u>OBJECT: Ramp</u>

DEFINITION: Area where paths of aircraft and vehicles are not specified such as parking areas, helicopter pads, etc. Identified by the nodes through which they may be accessed

PROPERTIES: Identifying nodes
Weight limit

6. <u>OBJECT: Gate</u>

DEFINITION: Special location for the loading and unloading of passengers and cargo

PROPERTIES: Identifying number
Location
Weight limit

7. <u>OBJECT: Aircraft</u>

DEFINITION: Flight vehicle which arrives and departs the airport over the runway and adheres to the defined path structure (as opposed to a helicopter)

PROPERTIES: Identification
Type
Weight
Gate or parking assignment
Flight plan

8. <u>OBJECT: Helicopter</u>

DEFINITION: Flight vehicle which is capable of moving over the airport surface without adhering to the defined path structure

PROPERTIES: Identification
Type
Weight
Flight plan

9. OBJECT: Surface Vehicle

DEFINITION: Non-flying vehicle which operates on the airport surface

PROPERTIES: Identification
Function
Capability

10. OBJECT: Taxi Route

DEFINITION: Combination of path segments which make up the components of a designated taxi route

PROPERTIES: Identification
Component path segments
Estimated occupancy time of component path segments

Other objects will be desirable, but the above listing is adequate to describe how some of the primary functions can be carried out.

5.3.4 Examples of Object-Oriented Programming

1. Conformance monitoring would be accomplished by verifying that the current path segment occupied by a vehicle was a component of the vehicles assigned taxi route.

2. Conflict prediction would be initiated by a search for taxi routes with common nodes or path segments, followed by a search of the common elements for overlapping occupancy times.

3. Conflict alert could be triggered whenever two aircraft or other vehicles were within some designated number of seconds from occupying the same path segment.

4. Runway incursion warnings could be issued to all aircraft within one path segment from an active runway. The nature of the warning could be made a function of aircraft speed and distance to the runway boundary.

5.3.5 Relationship to Airborne Logic

Taxi clearances which deliver aircraft to their take-off runway on time and in their proper order will require sophisticated logic. The structure that has been described above places the problem into the same format as enroute air traffic control. The problem reduces to a search for the best combination of available path segments which meet the constraints on time and order, given the existing clearances to other traffic. While the fundamental problem is not trivial, the important observation is that control of traffic

on the airport surface has much the same character as the control of airborne traffic. The taxiways are similar to the airways. Changing to a parallel taxiway is similar to assigning a different altitude. Holding on the ground can be done by stopping. Sequencing taxiing aircraft for take-off is similar to the process of sequencing airborne aircraft for landing. Getting an aircraft to the runway for take-off at a specified time is similar to getting an airborne aircraft to the landing fix at a specified time. An automation solution to these problems is currently being developed as part of enroute and terminal area automation. Those solutions should be readily adaptable to similar problems in airport surface control. If artificial intelligance provides useful results for airborne automation, the same techniques should prove useful for surface automation.

5.4 Man-machine Interface

5.4.1 Interface Techniques

The interface between the controller and the automation logic is probably the most challenging part of the system design. The primary way which the system communicates information to the human is through visual and audible means. The visual cues will probably be displayed on an airport map with alpha-numeric information available adjacent to an object symbol. An auxiliary display might be used if there is too much clutter. Audio cues can be in the form of computer-generated voice. The primary way in which the human communicates information to the system is through touch and voice. The input modes which involve touch include a touch sensitive display, a trackball or mouse, and a keyboard. The voice input will require automatic speech recognition. There are advantages to all of these communication modes, and at this point it appears reasonable to continue research and development with all of these input options available.

5.4.2 Display Information

The map display should show all the path segments appropriately scaled. The local controller, who is responsible for landing traffic starting from the outer marker about 5 miles out, already has an ARTS repeater which shows the airborne traffic. If the surface display were to extend 5 miles out, the projection of the taxiways would be too small. For this reason, the display will only show the airport surface. It will still be important to indicate the presence of landing traffic, but a prediction of touch-down time may be sufficient. Traffic operating under visual flight rules can normally be seen visually or with the aid of the ARTS repeater. The display of the airport surface is most useful to the local controller for clearing take-offs and landings on the runway and coordination with the ground controller who may need to clear aircraft or vehicles to taxi across the runway. The display shows all the areas of interest for the ground controller so long as it is obvious when the runway will be occupied by landing traffic. Consider the

scale of the map to be about 10^4 to one which causes a 10,000-foot runway to project with a one-foot length on the display. Dallas at this scale would require a display radius of about sixteen inches. Washington National would require only five inches. In practice it will be better to establish the display size and adjust the scale to include the desired area. The above example gives an indication of the size of display required. The type of information that needs to be displayed is indicated in Table 5.4. The visual information would be accompanied by computer-generated voice, particularly in the case of urgent alert warnings. Use of color is anticipated, particularly for alert and status functions.

5.4.3 Controller Input Techniques

In order for the automatic system to stay abreast of the control task, it must be kept informed of the controller's intent. Consequently, all information including every clearance has to be entered into the computer. The dissemination of so much information from a human operator to the computer may cause a breakdown in the use of current input modalities such as the keyboard, special function keys, the trackball and a mouse with pull-down menus [14]. Speech has a number of benefits over these existing modalities. It is easier, less demanding, and more natural. It requires little training while leaving the hands and eyes free for other tasks, such as multi-modal communication with simultaneous use of track ball, mouse, or keyboard. Speech is the highest capacity output channel for human-to-human communication. It is not clear that the same will be true for human-to-machine, but there is the potential for workload reduction. For repeated tasks, such as taxi route designation, it may be convenient to communicate the route by touch designation on the display screen. Speech input was studied as a substitute for keyboards in flight-strip entry and updating in 1977. Even with 10-year-old technology, the error rate was reduced. However, there was no significant difference in data entry rate. That system required pauses between words. Based on these arguments, it is recommended that the development of the man-machine interface proceed with all of the modalities mentioned above and only drop any of them when it has been demonstrated they are not used by the controller during simulation.

TABLE 5.4

INFORMATION TO BE DISPLAYED

Location and identification of all traffic in the movement area

Additional "On Demand" information for all indicated targets such as velocity, flight plan, etc.

Presence of off-scale landing traffic showing runway and estimated touch-down time

Listing of aircraft and location not in the movement area

Additional "On Demand" information for landing aircraft

Exit prediction for aircraft on runway

Route of taxi clearances

Dispatch or arrival of data link messages

Dispatch of digital billboard messages

Preview of automatic messages

Warning alerts for:

- Conflicting traffic
- Runway incursion
- Wake-vortex
- Wind shear
- Taxi non-conformance
- Equipment outages

Status indications of runways, taxiways, ramp, emergency equipment, etc.

Operational data on demand

Control menus for interfacing with computer

Text created by keyboard

Cursor for mouse or trackball

6. SPECIFICATION OF ASTA SIMULATION

The next step in the development of airport surface automation will be called the ASTA simulation. It will consist of a real-time, controller in the loop, simulated tower cab with an interactive display. Simulated aircraft and surface vehicles will follow their clearances except when blunder errors are introduced. Realistic sensor errors will be added to vehicle locations before processing the location data. Emphasis will be placed on the man-machine interface.

6.1 Objectives

The initial purpose of the ASTA simulation will be to develop the display and the man-machine interface. During development, the simulation will be used as a demonstrator for evaluation of the modules that make up the system. It could be used as a controller trainer prior to operational deployment. The simulator should be capable of representing any airport where it might ultimately be used. The capability of the system to switch from one airport representation to another should be demonstrable in the simulation. After operational deployment of ASTA, the simulation or upgraded versions of it could be used at the FAA Academy to familiarize controllers with the airports to which they were to be assigned. At any stage, the simulation should be useful for research on airport surface operations [15].

6.2 The Simulated Tower Cab Environment

6.2.1 Definition of Environment

The tower cab must operate with airport visibility so low that surface traffic cannot be seen visually from the tower. Under these conditions the ASTA display must be able to substitute for the visual view from the tower cab. Consequently, the simulation represents the tower environment when the outside view is obscured. Present towers already have an ARTS repeater which shows airborne traffic beyond the airport surface. The simulation will include an ARTS repeater in addition to the ASTA display of the airport surface. There will be no outside visual information other than from these two displays for purposes of the simulation.

6.2.2 Simulated Operation

It should be possible to operate the simulation with both the local controller and the ground controller active in order to understand the problem of coordination between their two positions. Landing aircraft will first appear on the ARTS repeater. Communications with simulated aircraft can be by voice or Mode S data link, assuming a mix of communications capability among the simulated aircraft. Normally, aircraft communication responses will be automatically generated as a Mode S data link reply or a computer-generated voice reply. The landing aircraft will acknowledge and carry out the clearances from the controllers and the ASTA system. This will cause their displayed targets to land and taxi to an appropriate gate assignment.

Departing aircraft will communicate with the simulated tower prior to the time for their departure to request clearance. Their response to tower clearances will cause their displayed targets to leave the gate area, taxi to their take-off runway, take-off, and depart. Ground vehicles will request their clearances over a separate voice radio channel on a random basis. The scheduling of ground vehicle traffic will require a survey of ground vehicle patterns at the individual airport.

6.3 Aircraft Scheduling

6.3.1 Arriving Aircraft

Arriving aircraft will be scheduled for their approach starting at the ILS outer marker inbound on final. From that point on, the displayed motion will depend upon clearances given to the aircraft by the ASTA system as operated by the subject controller. The nominal landing schedule will be taken from the Official Airline Guide (OAG) using the scheduled arrival time less fifteen minutes as the simulation time over the outer marker. The desired spacing between aircraft at the outer marker should be designated by the subject controllers; simulating the capacity estimate they forward to flow control. The nominal landing schedule will be adjusted to produce the designated spacing while maintaining the nominal order. If there are too few scheduled landings, "pop-up" general aviation traffic will be inserted. Should there be too many scheduled landings, a queue will be formed preserving the nominal order. This procedure provides a simulation of the flow control process as it is intended to work.

6.3.2 Departing Aircraft

Departing aircraft will request clearance at their scheduled departure time. The nominal take-off schedule will be based on the departure time listed in the OAG plus fifteen minutes. The desired spacing for take-offs will also be designated by the subject controllers. The nominal take-off schedule will be adjusted to produce the designated spacing while maintaining the nominal order. If there are insufficient scheduled departures, "pop-up" general aviation departures will be inserted. If there are too many scheduled departures, a queue will be formed preserving the nominal order. If a departing flight has been delayed in landing, its departure time will be advanced by the time delayed. This adjusted take-off schedule will simulate the desired take-off times that would be received from departure flow management. It will be the goal of the controller's to match actual take-off times achieved to the desired times generated in response to the capacity they established when they declared the desired take-off spacing.

6.3.3 Aircraft Identification and Type

The aircraft call sign is the same as the flight identification given in the OAG. The aircraft type as listed in the OAG will be used to determine landing speed.

6.4 Motion Generation

Landing aircraft will proceed as cleared along the path specified in their clearance at an air speed selected from a normal distribution for the aircraft type. The standard deviation, σ_v, will be five percent of the average air speed. The ground speed will be obtained from the air speed by adding or subtracting the appropriate along-track wind speed component. Deceleration will be selected from a normal distribution with

$$\bar{a} = 5 \text{ ft/sec}^2 \qquad \sigma_a = 0.05\ \bar{a}$$

Taxi speed will be selected from a normal distribution with

$$\bar{v} = 30 \text{ ft/sec} \qquad \sigma_v = 0.05\ \bar{v}$$

Take-off acceleration will also be taken from a normal distribution with

$$\bar{a} = 10 \text{ ft/sec}^2 \qquad \sigma_a = 0.05\ \bar{a}$$

All normal motion will follow the path specified by a clearance. Deceleration of a landing aircraft starts where the glide slope intersects the runway. Unless cleared otherwise, an aircraft will exit the runway at the first exit after it reaches taxi speed. Taxiing aircraft will maintain an interval of 200 feet behind aircraft taxiing ahead of them. Aircraft follow their clearances until reaching the gate where their target symbol is removed. Departing aircraft follow their clearances to the departure runway, where they hold until being cleared for take-off. Then they accelerate along the runway until their target symbol is off-scale. Ground vehicles proceed in a manner similar to taxiing aircraft, but do not normally go to the departure runway. In general, all normal motion is along a path specified by a clearance. The exception to this will be called "blunder motion" and will be treated separately in the next section.

6.5 Blunder Motion

Blunder motion is defined as any simulated motion that is not the motion specified in a clearance. The purpose of blunder motion is to set up situations that will challenge the security provided by ASTA alerts and controller response. Establishing blunder situations will require clever design. Generating blunder motion, however, is relatively simple since all that is needed is to create a bogus clearance that is different from the intended clearance and to have the target motion be driven by the bogus clearance. The type of blunder situations which can be created are indicated in the following examples:

Aircraft or vehicle proceeds without clearance
Aircraft or vehicle proceeds beyond clearance limit
Aircraft or vehicle follows someone else's clearance

There are also unusual situations which are not blunders, but would be simulated by using blunder motion. Examples of these are:

Landing aircraft executes missed approach
Aircraft aborts take-off and stops on runway
Taxiing aircraft comes to a stop

There will probably be blunder situations that are not created by blunder motion. Any errors committed by ASTA or the subject controllers should fall into this category. These will be called "unplanned blunders". There will also be two categories of planned blunders. Blunders will be generated by the computer at randomly selected times or will be created by placing a human pseudo-pilot in the simulation to move his aircraft target and talk on the radio. The simulation should be capable of operating all of these planned blunders.

6.6 Alerts

Alert warnings should be created in the simulation exactly as they would for the actual ASTA system. The scheduler, motion generator, and blunder generator are artifacts for making the displayed targets look like the real world. What is done with the target information in the simulation should be the same as what the ASTA system would do with the real world information. The alert warnings which have been specified include:

Runway incursion
Non-aircraft runway intruder
Taxi conformance violation
Conflict alert
Wake-vortex warning

The last warning would require the wind direction and magnitude as input. The others can all be based on information developed as part of the input clearances and simulated motion.

6.7 Imbedded Performance Analysis

6.7.1 Purpose

The ASTA simulation should have incorporated within it the capability to evaluate the performance of the subject controllers using the ASTA design when the simulation is excercised. The primary areas of interest for performance improvements are safety, capacity, and delay. Performance assessment features are discussed for each area.

6.7.2 Safety

In the safety area, all of the features available in the current system should be present. There should be tapes of all the communications, surveillance, and clearances. In addition, there should be scan-by-scan printouts of every runway incursion and taxi conflict, showing relative positions and times of caution advisories and warning directives. The simulation should have the capability for stop action, instant replay and reset. Some measure of controller workload should be present, preferrably more than one measure. There should be a tabulation of all alarms given by type, number of voice communications, and data link messages.

6.7.3 Capacity

In the capacity area, the main performance measure is the throughput achieved relative to the prediction. Numbers of take-offs, landings, and missed approaches should be available as a function of time and traffic mix. Runway and taxiway occupancy times should be recorded for analysis.

6.7.4 Delay

For the study of delay, the main performance measure is the on-time delivery of aircraft to the take-off runway. Statistical information on delays at the gate, at the runway, and while taxiing are of interest. Several capacity measures also contribute to delay performance. Examples of this are the number of missed approaches and the ability of the controllers to predict accurately the achievable throughput.

7. SUMMARY OF FINDINGS

7.1 Functions and Priorities

The necessary functions to be accomplished in the implementation of an Airport Surface Traffic Automation System and their priority is as follows:

1. Establish improved surface surveillance and communication between the automation and the traffic.

2. Create automatic conflict alert and collision avoidance warnings for both pilots and controllers in order to reduce the risk of collision due to runway incursion or taxiway conflict.

3. Provide strategic and tactical planning assistance to controllers which will allow them to obtain maximum runway utilization for the existing conditions.

4. Improve controller productivity by automating the process of clearance delivery so that the controller only needs to give approval or indication of intent.

7.2 Safety Benefits

The greatest benefit associated with the ASTA system is improved safety with regards to runway incursion accidents. The federal government is responsible for making public air transportation safe. The public perception of air safety outweighs the economic losses to aviation accidents when evaluating the government's performance. While the cost saving would be large, the potential benefit of avoiding a fatal accident of this kind is far more valuable than the dollar cost of the loss.

7.3 Cost Benefits

The total cost of delays in 1986 was over $2 billion. Increasing demand will increase the cost due to delays at a percentage rate that is at least three times the percentage rate at which the demand increases. To reduce or eliminate the cost due to delay, several aspects of surface automation must participate. However, it cannot be accomplished by surface automation alone. The programs providing automation improvements to other interacting parts of the ATC system will require surface automation improvements for their success in reducing delay.

7.4 Airport Graphical Representation

A study was conducted of the airport diagrams for the 25 busiest air carrier airport traffic control towers. Statistical data was tabulated on the size and geometry of the airport surface. It was found that the surface of the airport could be constructed graphically by a number of path segments

joining nodes which represented the center of runway and taxiway intersections. Using this structure runways and taxiways can be designated as an ordered set of path segments. The structure provides a framework for carrying out automated surface control. The number of path segments for airports of interest was in the range of 50-250. The exercise showed that it is feasible to design a modular system that is adaptable to a specific airport geometry.

7.5 Initial System Design

A modular design for automation of the airport surface was initiated based on the necessary functions described earlier. It was concluded that the controller needs to stay in the loop and remain responsible for decision making. The automation provides warnings, advice and assistance, but the controller must give approval before automatic actions are taken. It was observed that the path segment structure chosen to represent the airport surface makes the control structure completely analogous to enroute air traffic control. Consequently, object oriented programming and all the research findings associated with the use of Artificial Intellignece technology in enroute ATC can be applied directly to the surface control problem.

7.6 Development Approach

The next steps in the design of ASTA are the development of the surveillance and communication system plus a controller-in-the-loop simulation of the man-machine interface. The two steps can proceed independently.

7.6.1 Surface Surveillance and Communication Approach

The best candidate for the improved surface surveillance and communication system is one using multilateration of a Mode S interrogation response. Multilateration eliminates the ± 125 ft error due to response time bias in the transponder. The system would permit identify tagging of ASDE radar targets, allow data link communication, and support runway incursion warning. The improved surveillance and communication system is necessary in order to carry out other functions of ASTA and should be given the highest priority.

The required accuracy of the surveillance data is about 25 ft, one sigma. Update rate of one second is desired with possibly higher rates for aircraft detected to be in conflict situations. The accuracy requirement is driven by the need to resolve two aircraft stopped adjacent to one another. The update rate requirement is driven by the need for accurate velocity information in conflict situations.

7.6.2 System Simulation

The interface between the controller and the automation logic is probably the most challenging part of the system design. The input modes include keyboard, touch-sensitive display, trackball or mouse, and automatic speech recognition. All information including every clearance must be entered into the computer. All of the interface modalities mentioned above should be evaluated.

Specification of the simulated tower cab is given in Chapter 6. The simulation represents the tower environment with the outside view obscured. Blunder situations are generated to test both the automatic and human elements. They can be initiated at random or by human intervention. Normal operations are conducted at the demand level specified by the operator. The simulator is to be designed to accommodate any specific airport and has additional applications to both training and research. It is intended to include all the functions that will be present in the actual system except the surveillance and communication functions, which are simulated.

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APPENDIX A

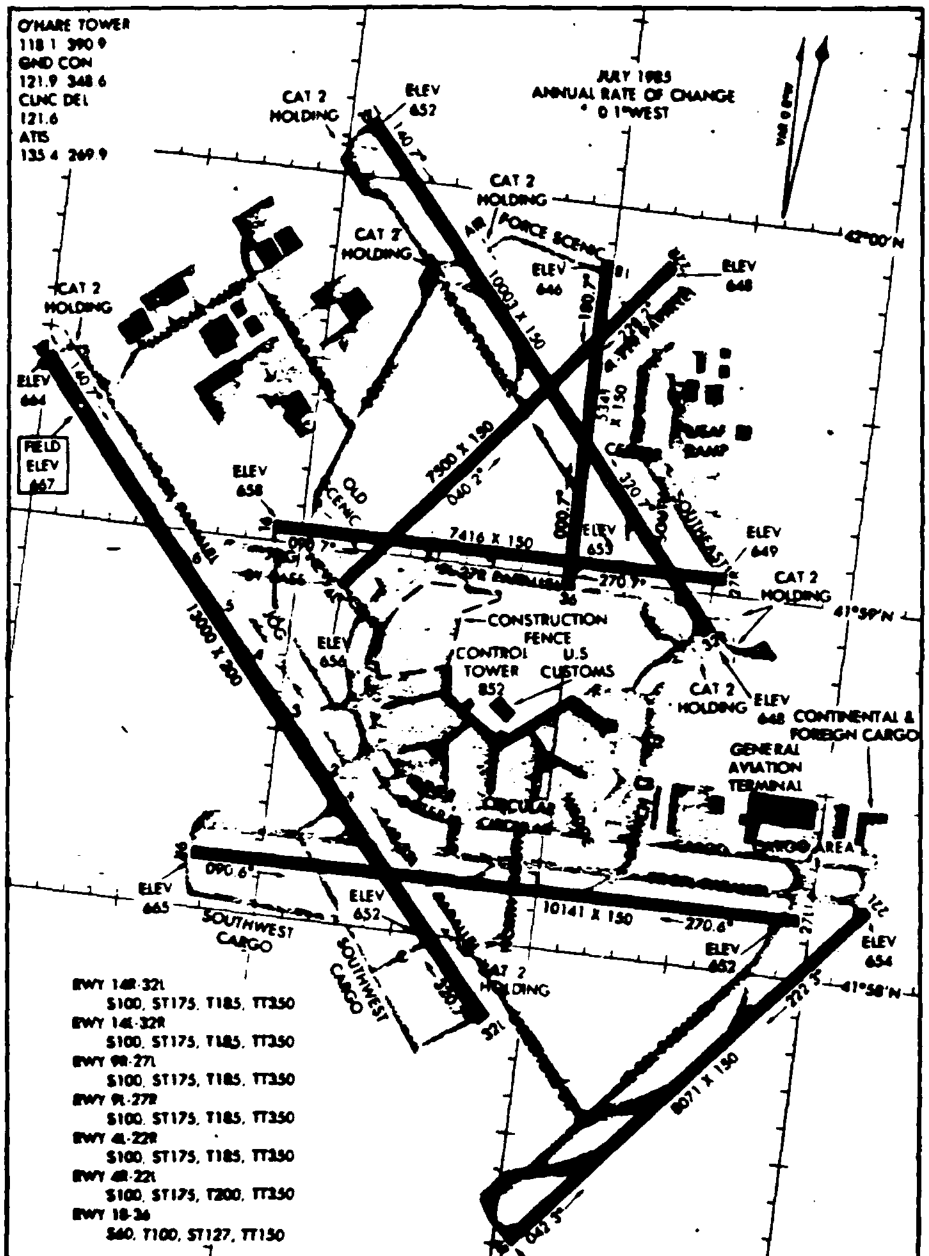
This appendix gives the airport diagrams for the 25 busiest, FAA-operated air carrier airport traffic control towers as listed in the FAA Statistical Handbook of Aviation for Calendar Year 1984. The airport diagrams are reproduced from U.S. Government Flight Information Publications.

AIRPORT DIAGRAM

42

AL-166 (FAA)

CHICAGO-O'HARE INTL (ORD)
CHICAGO, ILLINOIS



AIRPORT DIAGRAM

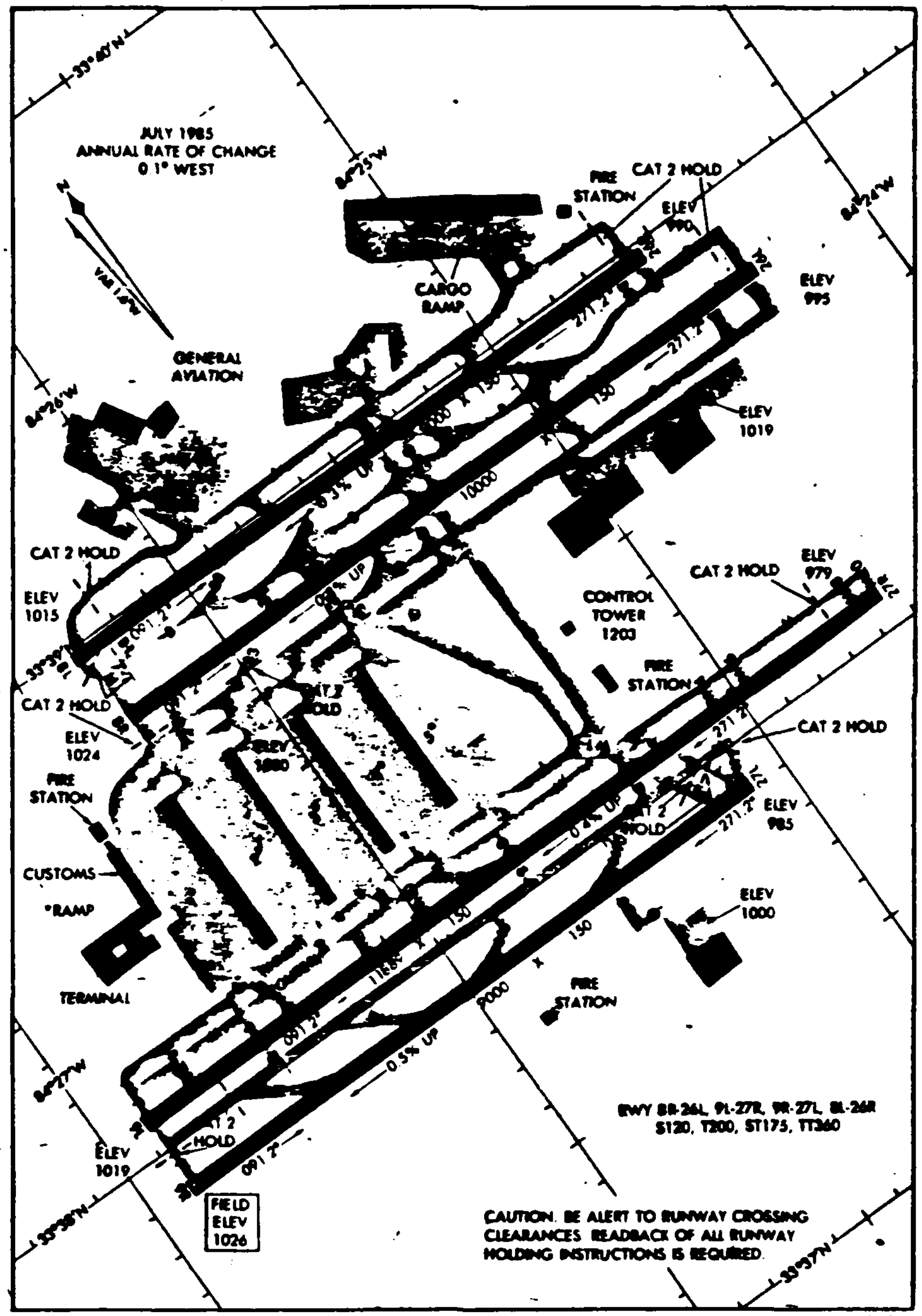
CHICAGO, ILLINOIS
CHICAGO-O'HARE INTL (ORD)

AIRPORT DIAGRAM

ATLANTA/THE WILLIAM B. HARTSFIELD ATLANTA INTL (ATL)

AL-26 (FAA)

ATLANTA, GEORGIA



AIRPORT DIAGRAM

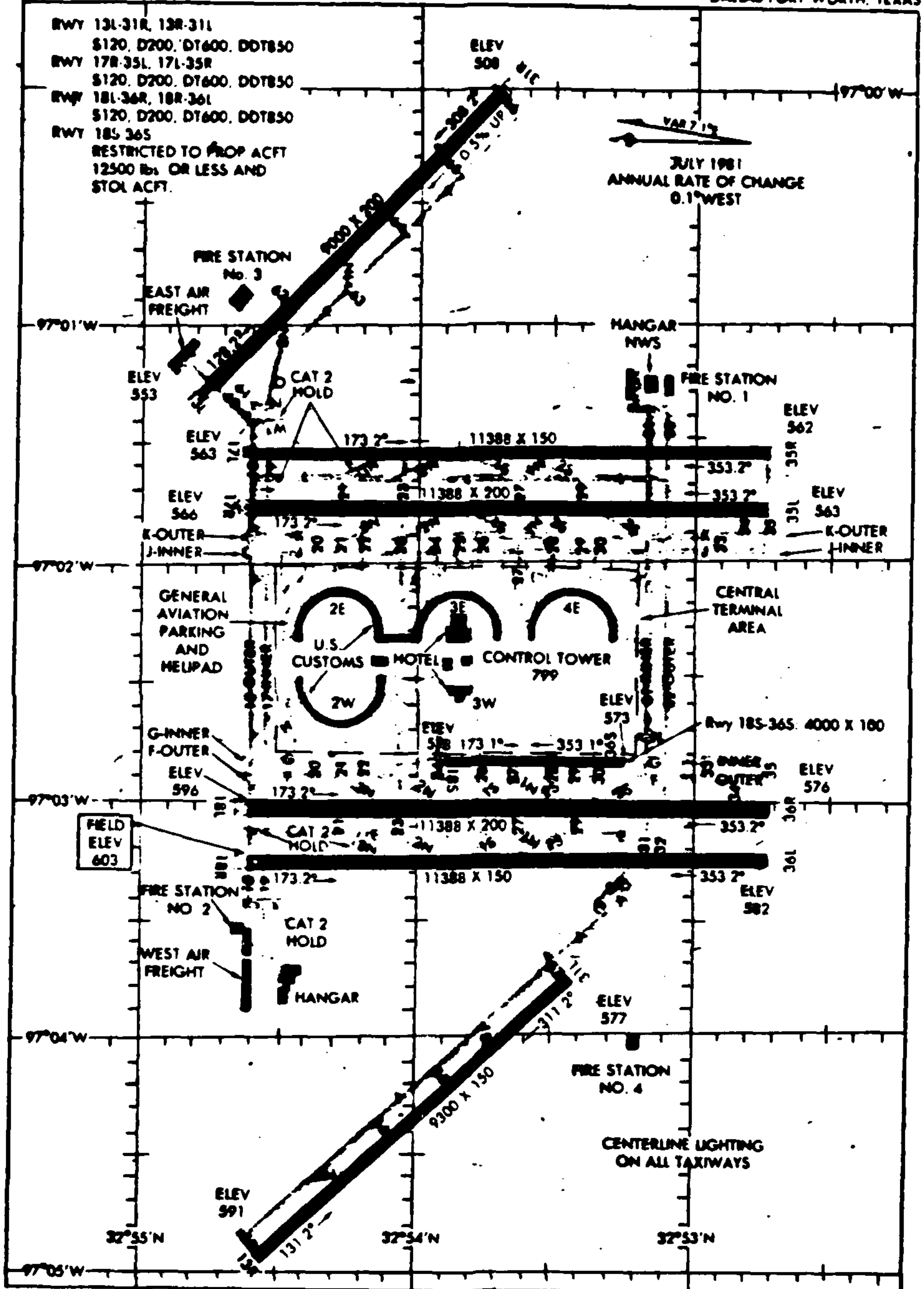
ATLANTA, GEORGIA

ATLANTA/THE WILLIAM B. HARTSFIELD ATLANTA INTL(ATL)

AIRPORT DIAGRAM

AL-6039 (FAA)

DALLAS-FORT WORTH INTL (DFW)
DALLAS-FORT WORTH, TEXAS



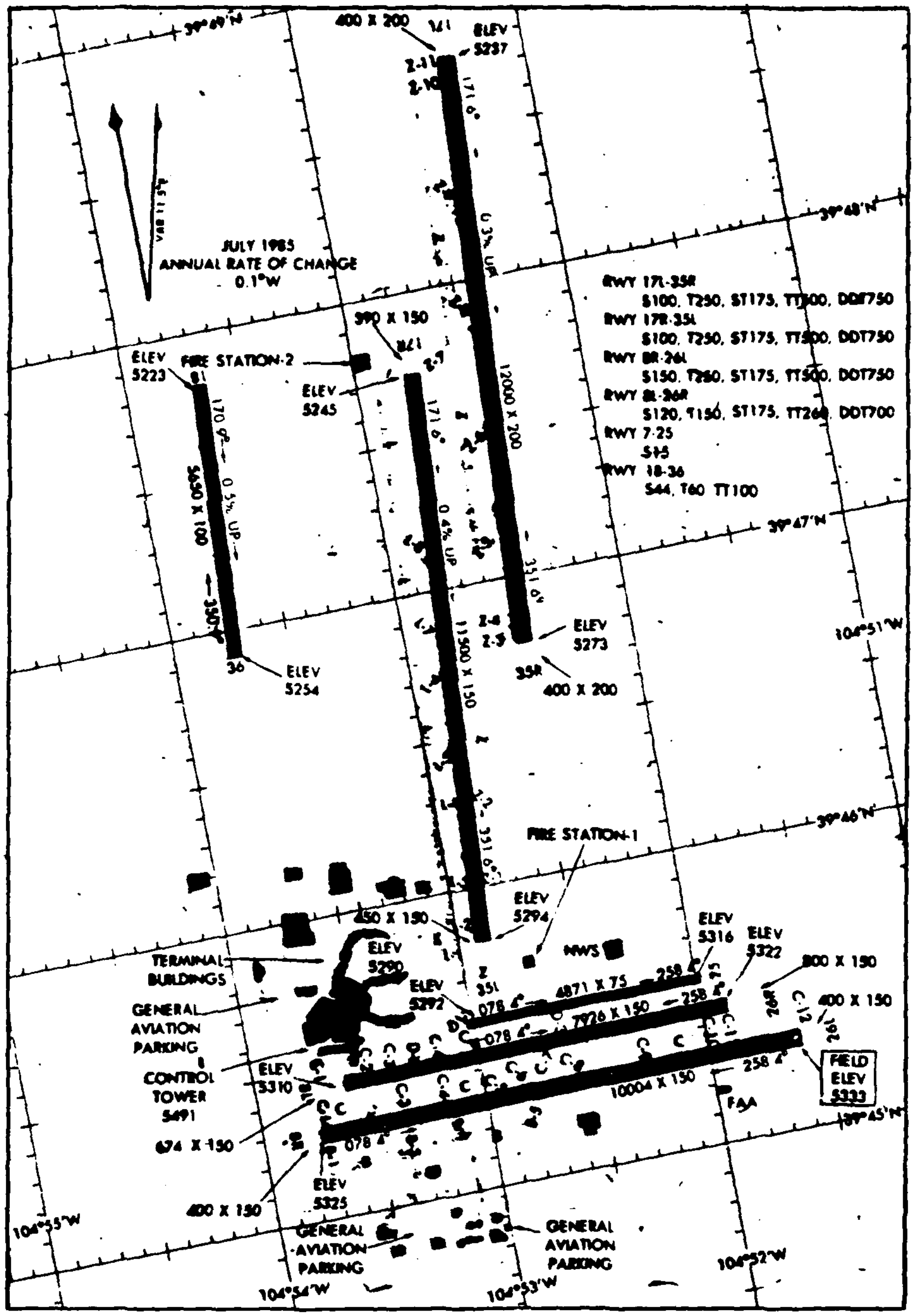
AIRPORT DIAGRAM

DALLAS-FORT WORTH, TEXAS
DALLAS-FORT WORTH INTL (DFW)

AIRPORT DIAGRAM

AL-114 (FAA)

DENVER/STAPLETON INTL AIRPORT (DEN)
DENVER, COLORADO

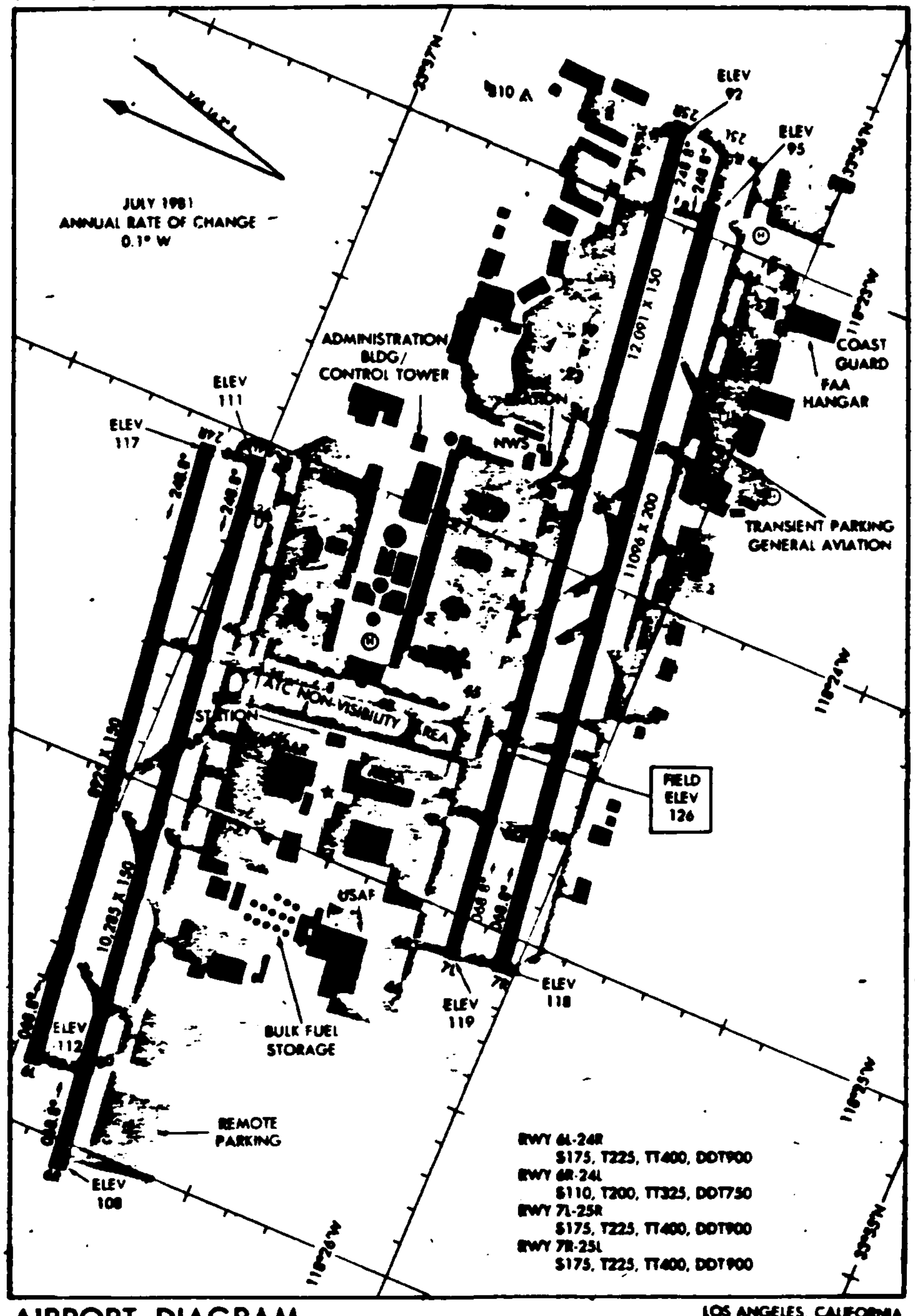


AIRPORT DIAGRAM

DENVER, COLORADO

105 DENVER/STAPLETON INTL AIRPORT (DEN)

AIRPORT DIAGRAM AL-237 (FAA) LOS ANGELES INTERNATIONAL AIRPORT (LAX) LOS ANGELES, CALIFORNIA



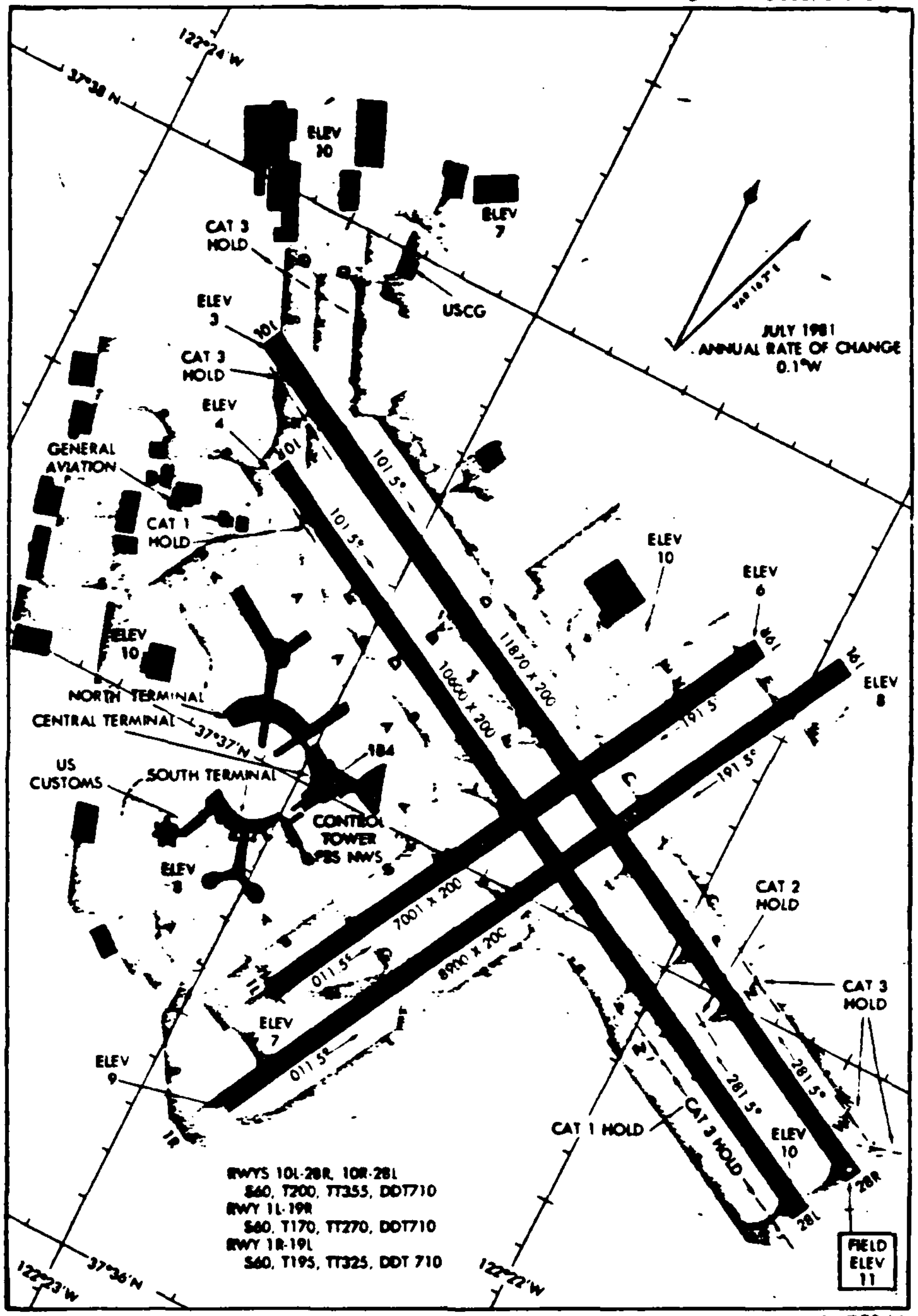
AIRPORT DIAGRAM LOS ANGELES, CALIFORNIA
165 LOS ANGELES INTERNATIONAL AIRPORT (LAX)

AIRPORT DIAGRAM

314 SAN FRANCISCO INTERNATIONAL AIRPORT (SFO)

AL-375 (FAA)

SAN FRANCISCO, CALIFORNIA



AIRPORT DIAGRAM

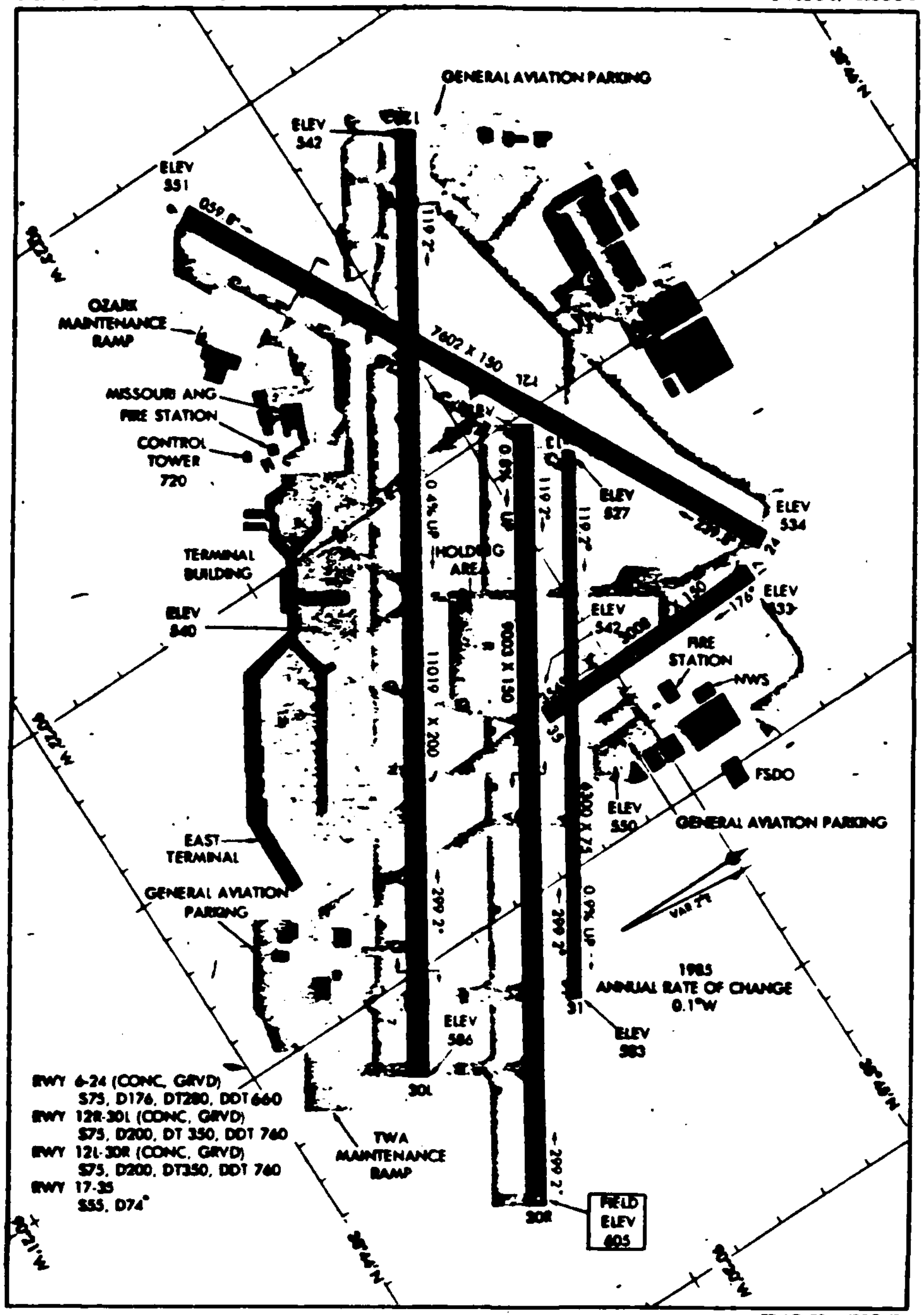
SAN FRANCISCO, CALIFORNIA

SAN FRANCISCO INTERNATIONAL AIRPORT (SFO)

AIRPORT DIAGRAM

344
AL-360 (FAA)

ST. LOUIS/LAMBERT-ST. LOUIS INTL (STL)
ST. LOUIS, MISSOURI



RWY 6-24 (CONC, GRVD)
S75, D176, DT280, DDT 660
RWY 12R-30L (CONC, GRVD)
S75, D200, DT 350, DDT 760
RWY 12L-30R (CONC, GRVD)
S75, D200, DT350, DDT 760
RWY 17-35
S55, D74

AIRPORT DIAGRAM

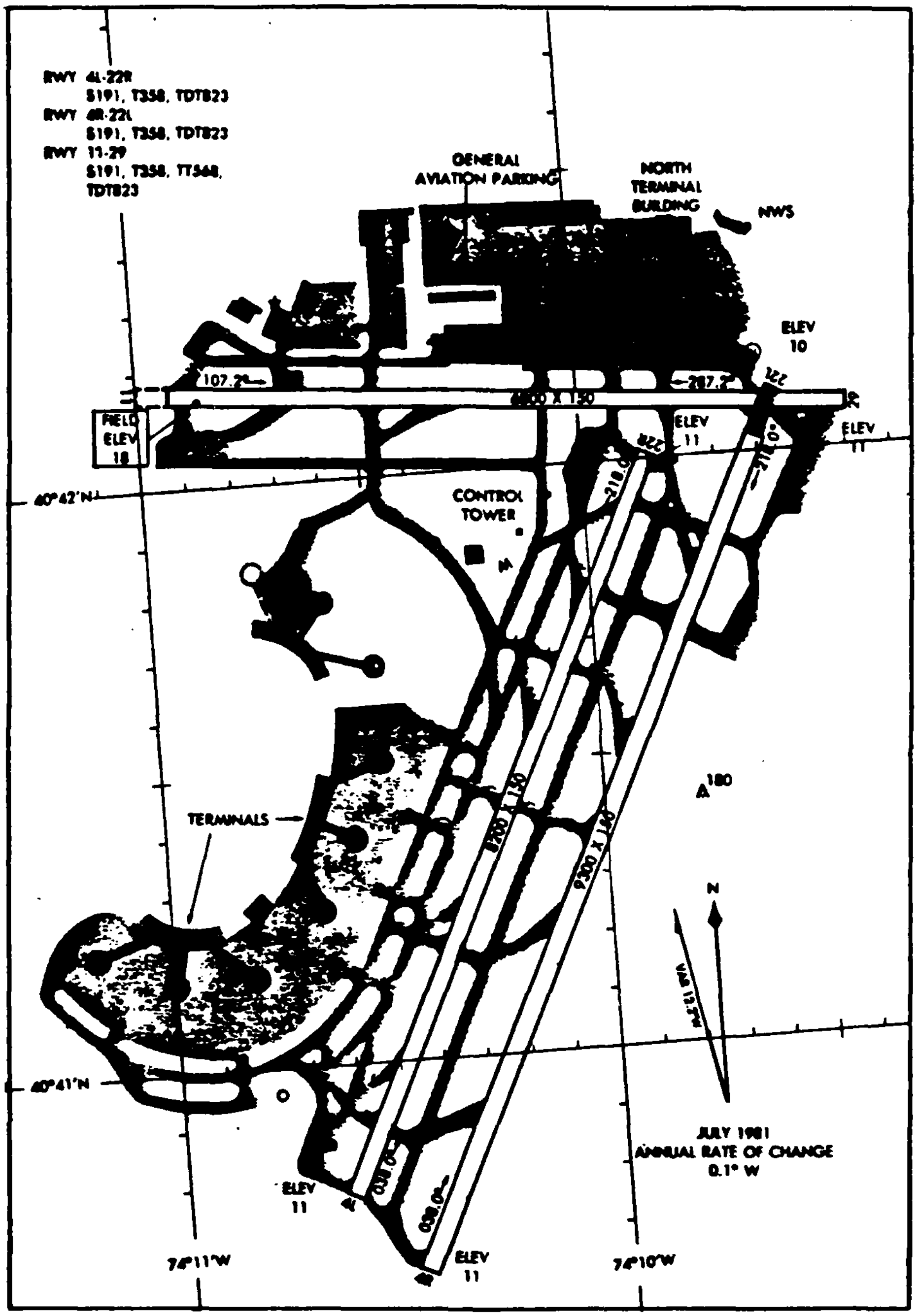
ST. LOUIS, MISSOURI
ST. LOUIS/LAMBERT-ST. LOUIS INTL (STL)

184

AIRPORT DIAGRAM

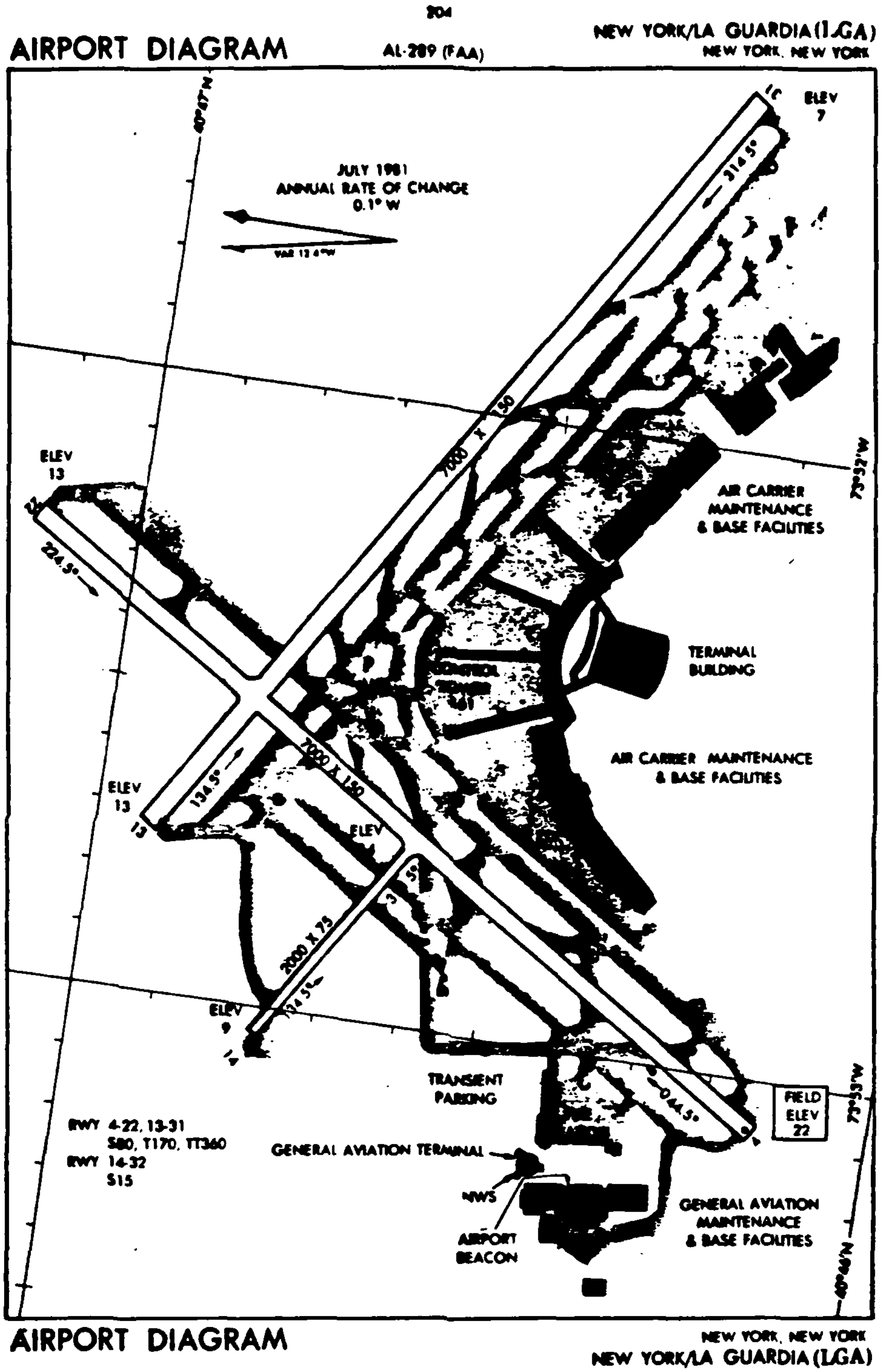
AL-285 (FAA)

NEWARK INTERNATIONAL (EWR)
NEWARK, NEW JERSEY

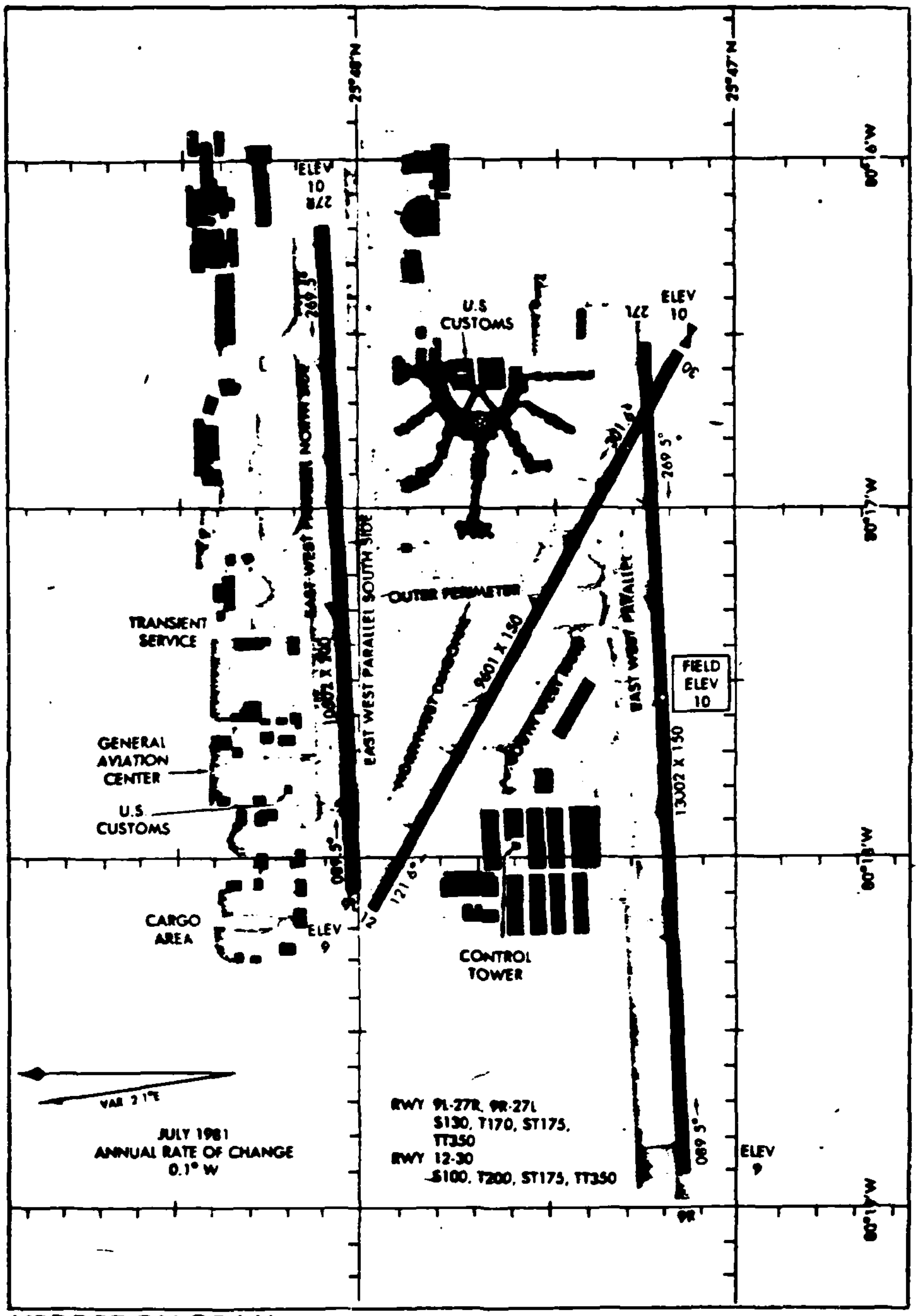


AIRPORT DIAGRAM

NEWARK, NEW JERSEY
NEWARK INTERNATIONAL (EWR)


204
AIRPORT DIAGRAM
AL-289 (FAA)
NEW YORK/LA GUARDIA (LGA)
NEW YORK, NEW YORK
JULY 1981
ANNUAL RATE OF CHANGE
0.1° W
ELEV
7
ELEV
13
ELEV
13
ELEV
9
AIR CARRIER
MAINTENANCE
& BASE FACILITIES
TERMINAL
BUILDING
AIR CARRIER MAINTENANCE
& BASE FACILITIES
7000 X 150
TRANSIENT
PARKING
FIELD
ELEV
22
RWY 4-22, 13-31
S80, T170, TT360
RWY 14-32
S15
GENERAL AVIATION TERMINAL
NWS
AIRPORT
BEACON
GENERAL AVIATION
MAINTENANCE
& BASE FACILITIES
AIRPORT DIAGRAM
NEW YORK, NEW YORK
NEW YORK/LA GUARDIA (LGA)

AIRPORT DIAGRAM AL-257 (FAA) MIAMI INTERNATIONAL AIRPORT (MIA)
MIAMI, FLORIDA

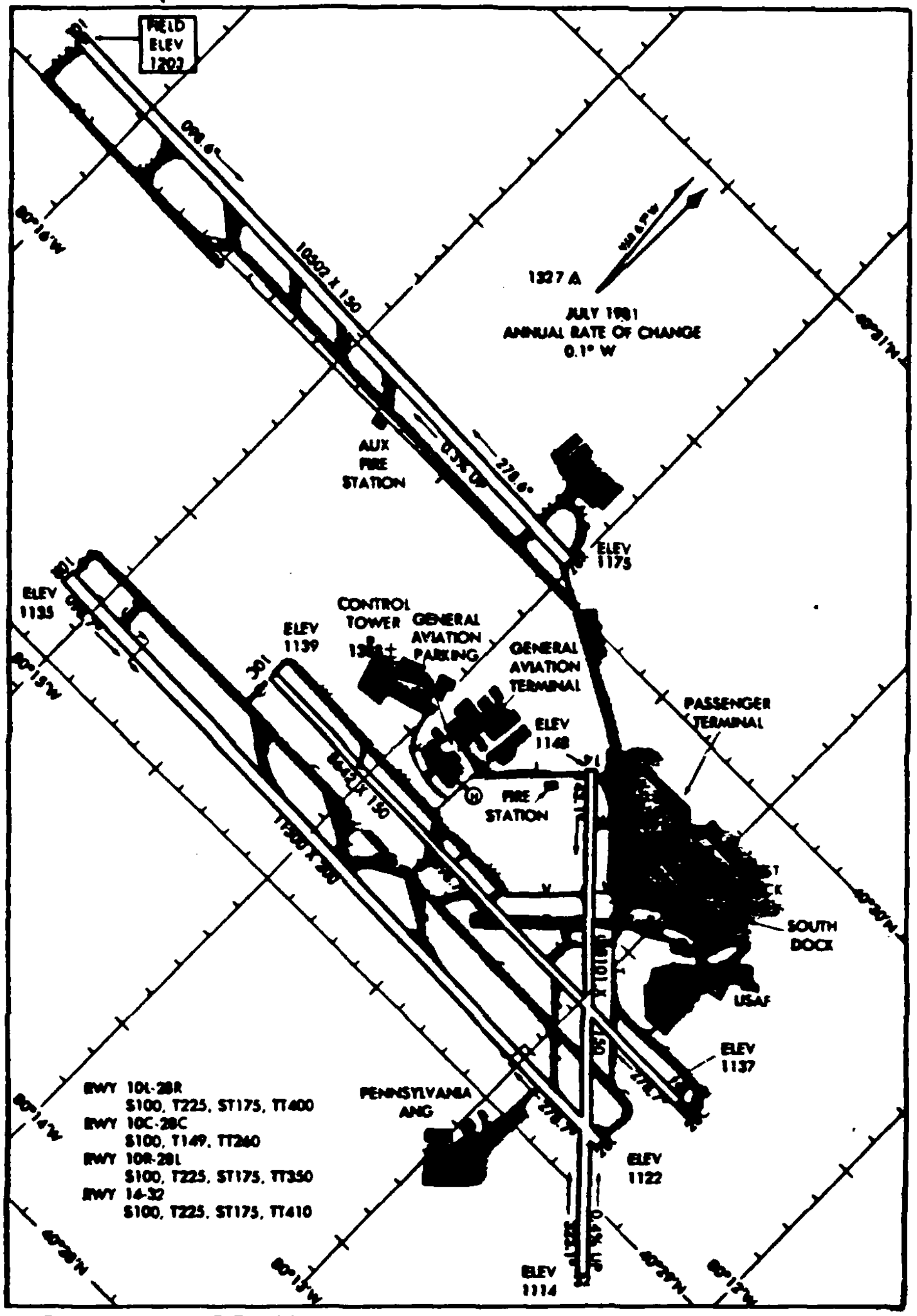


AIRPORT DIAGRAM 233 MIAMI, FLORIDA
MIAMI INTERNATIONAL AIRPORT (MIA)

262

AIRPORT DIAGRAM

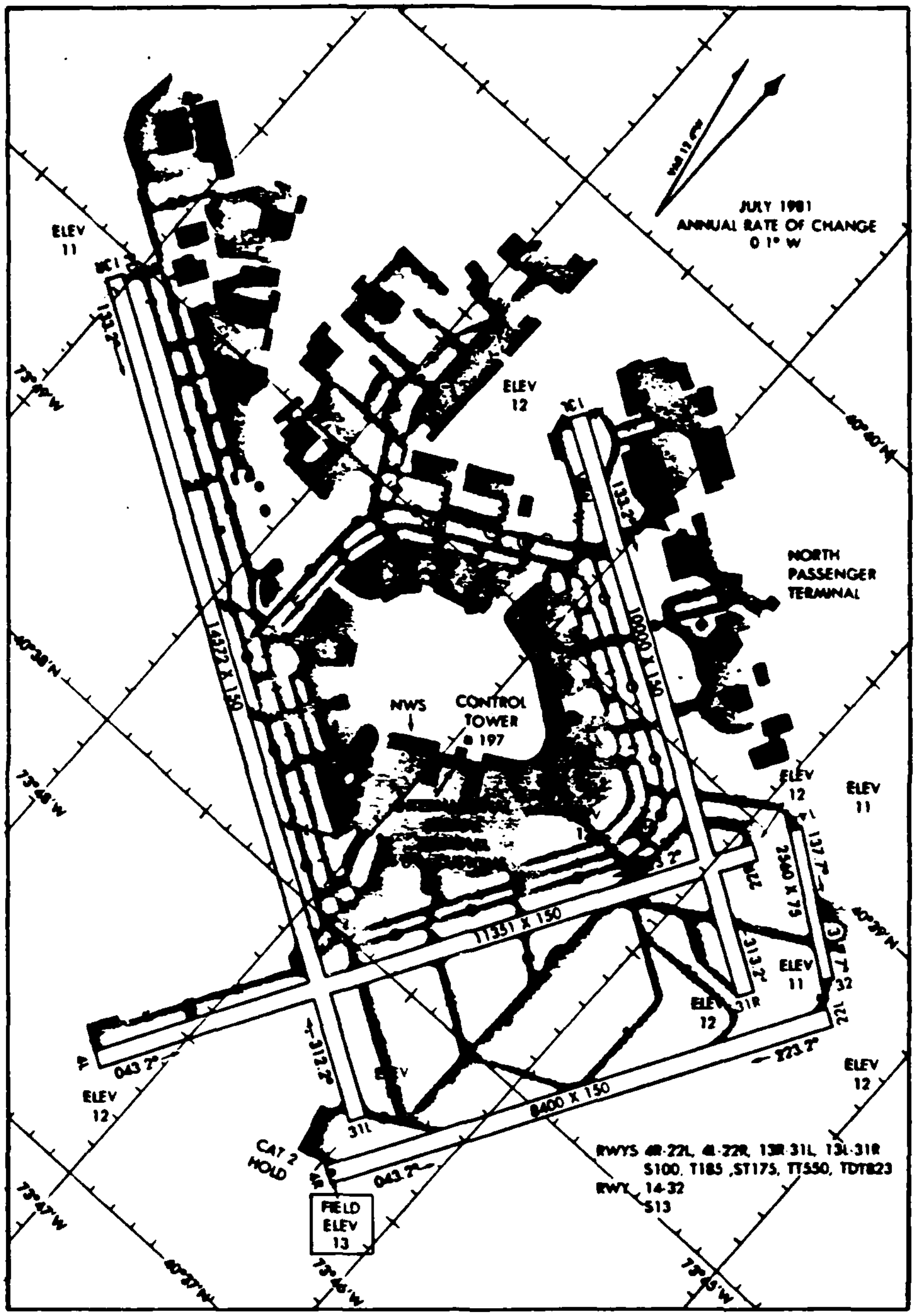
PITTSBURGH/GREATER PITTSBURGH INTL (PIT)
AL-570 (FAA)
PITTSBURGH, PENNSYLVANIA



AIRPORT DIAGRAM

PITTSBURGH, PENNSYLVANIA
PITTSBURGH/GREATER PITTSBURGH INTL (PIT)

AIRPORT DIAGRAM AL-610 (FAA) NEW YORK/JOHN F. KENNEDY INTL (JFK)
NEW YORK, NEW YORK



AIRPORT DIAGRAM NEW YORK, NEW YORK
NEW YORK/JOHN F. KENNEDY INTL (JFK)

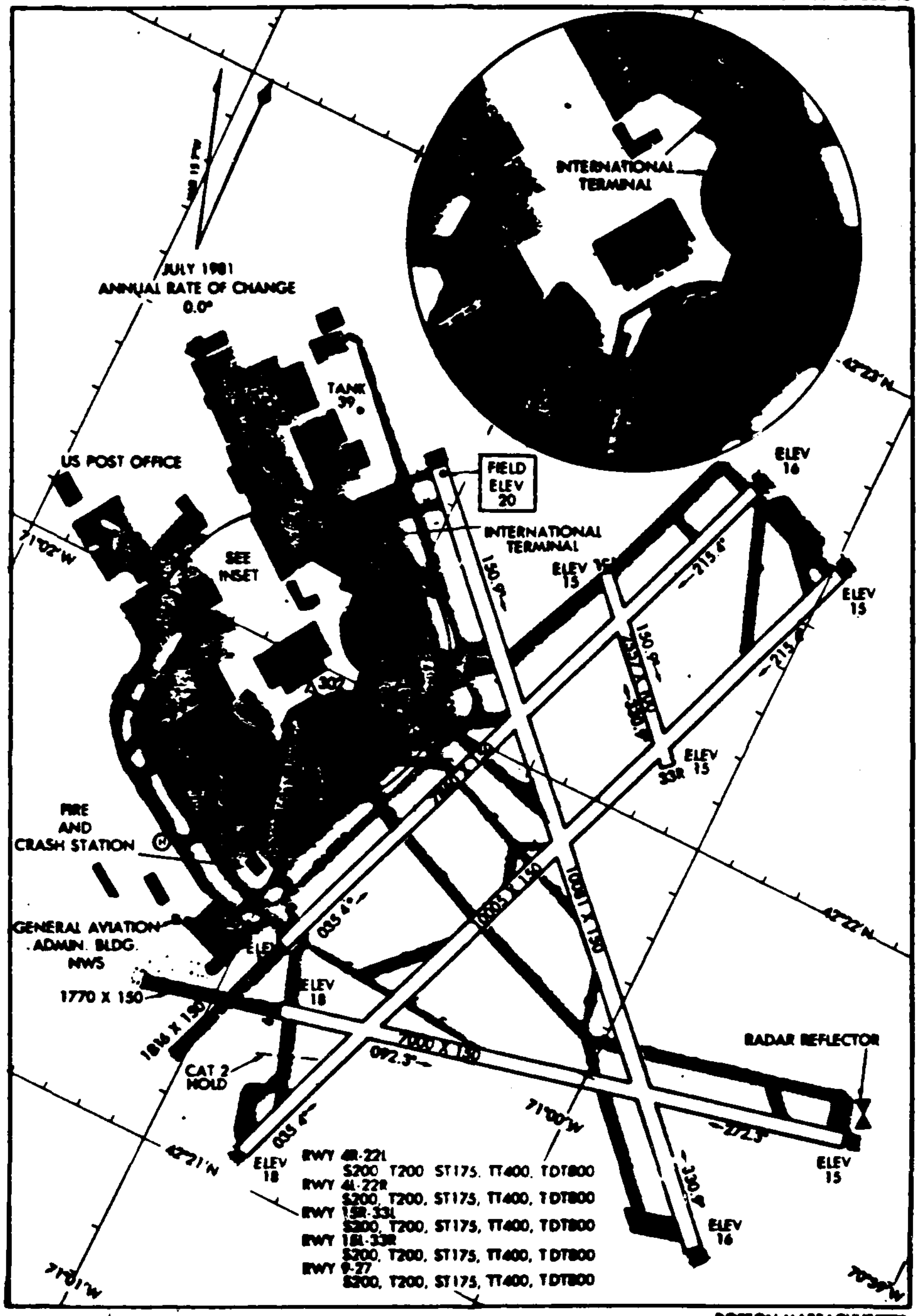
191

52
BOSTON/GENERAL EDWARD LAWRENCE LOGAN INTL (BOS)

AIRPORT DIAGRAM

AL-58 (FAA)

BOSTON, MASSACHUSETTS



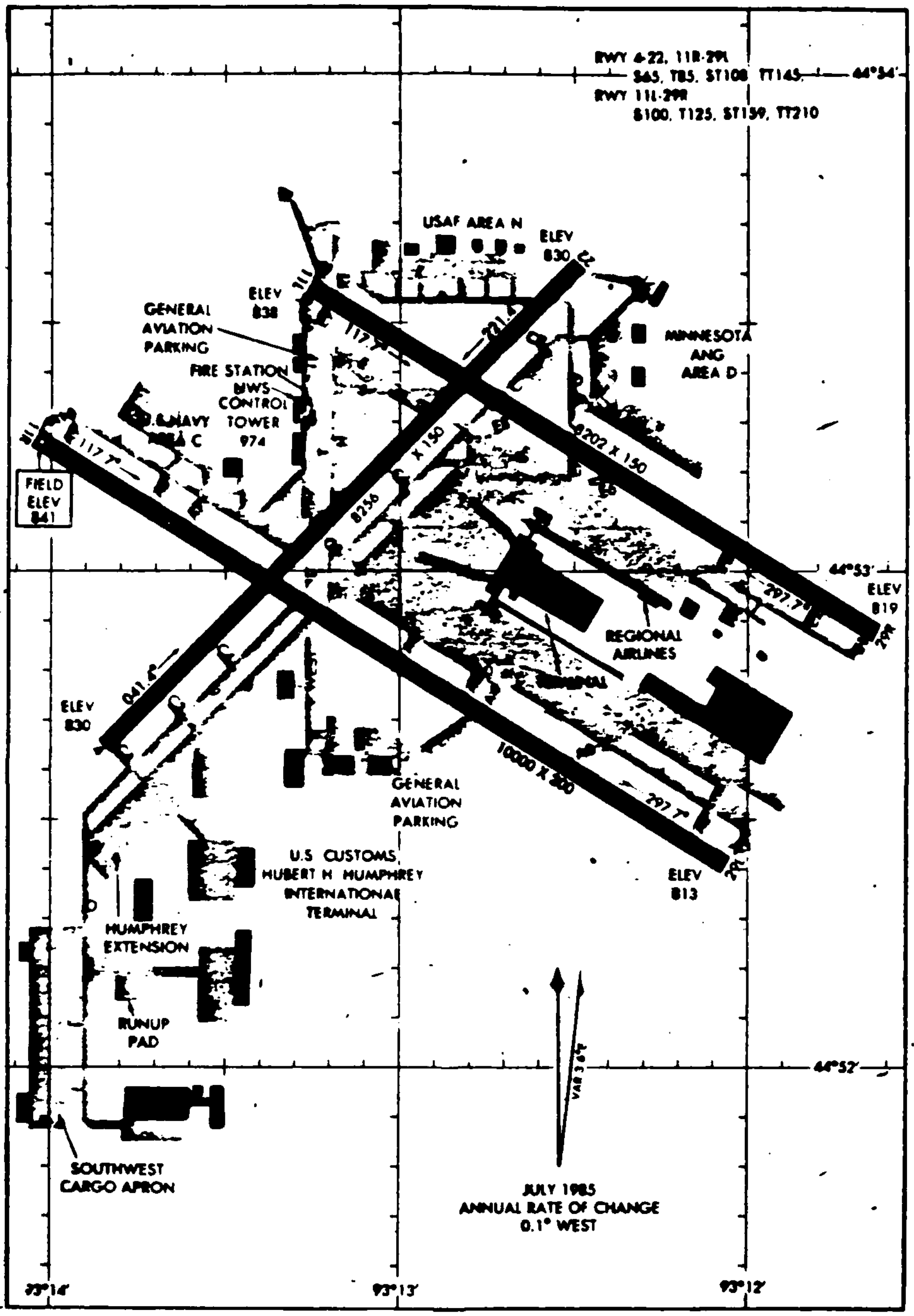
AIRPORT DIAGRAM

BOSTON, MASSACHUSETTS

BOSTON/GENERAL EDWARD LAWRENCE LOGAN INTL (BOS)

AIRPORT DIAGRAM

MINNEAPOLIS-ST PAUL INTL (WOLD-CHAMBERLAIN FIELD) (MSP)
AL-264 (FAA)
MINNEAPOLIS, MINNESOTA



AIRPORT DIAGRAM

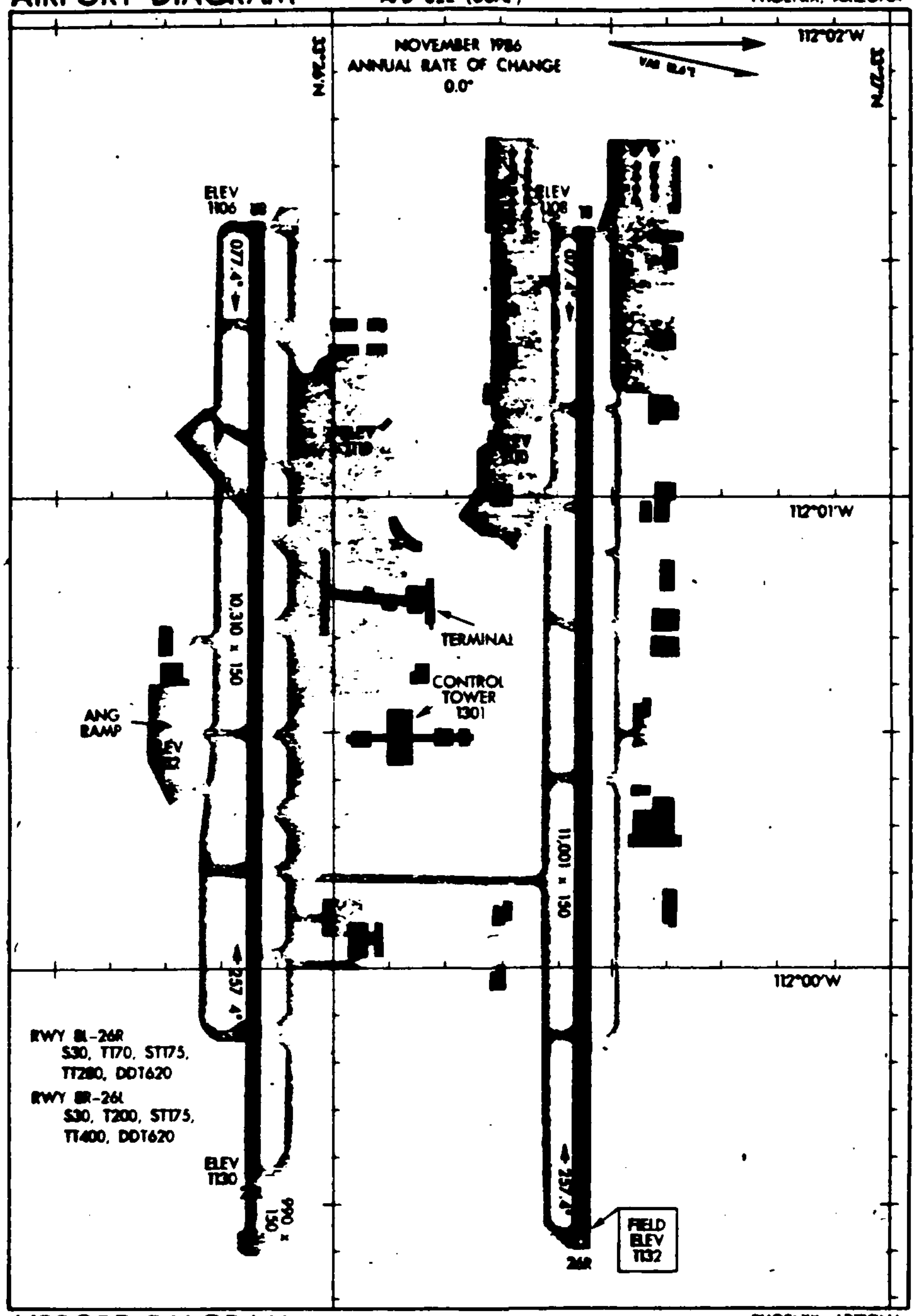
199
MINNEAPOLIS, MINNESOTA
MINNEAPOLIS-ST PAUL INTL (WOLD-CHAMBERLAIN FIELD) (MSP)

240

AIRPORT DIAGRAM

AFD-322 (USAF)

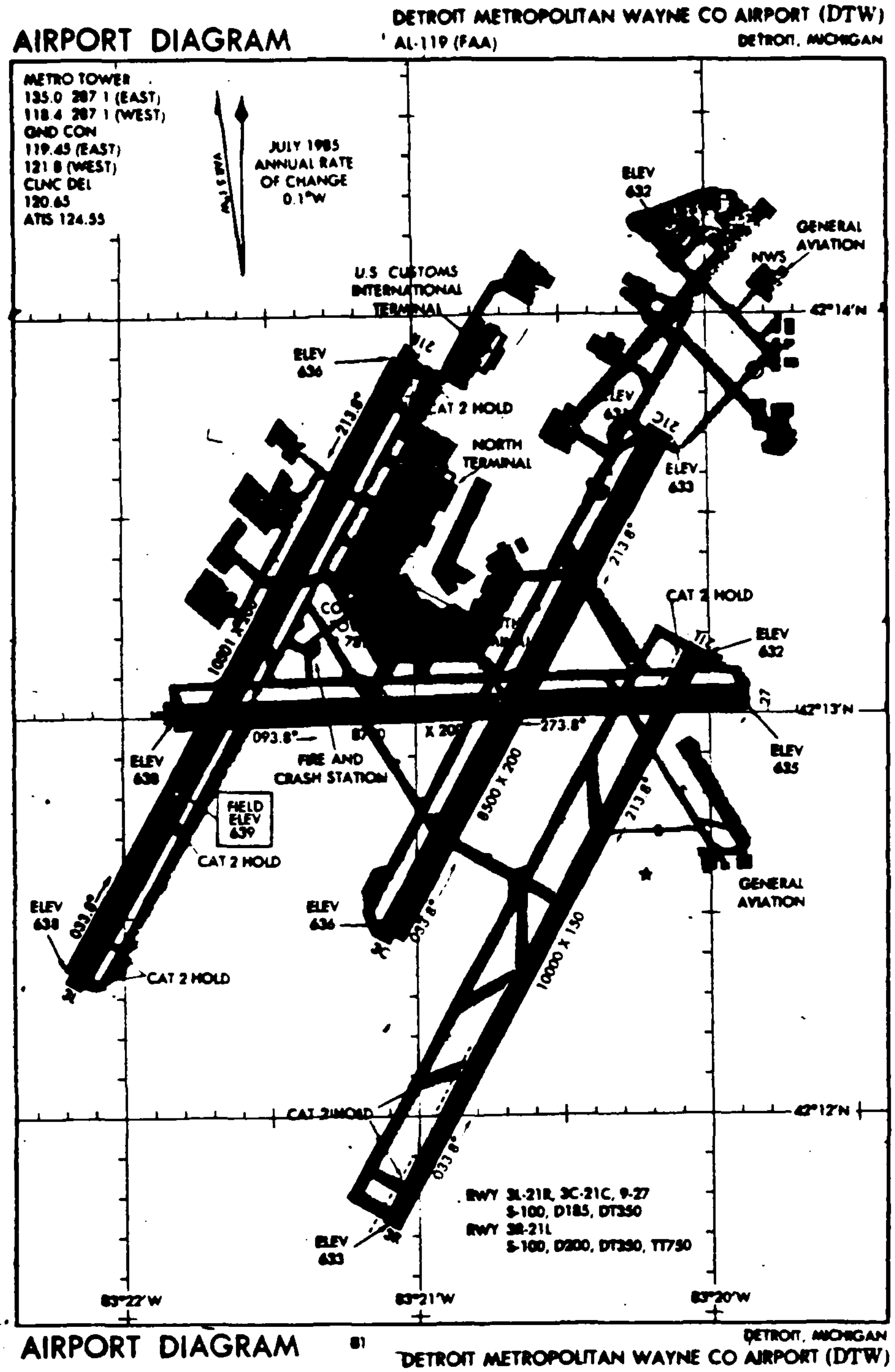
PHOENIX SKY HARBOR INTL (KPHX)
PHOENIX, ARIZONA



AIRPORT DIAGRAM

PHOENIX, ARIZONA
PHOENIX SKY HARBOR INTL (KPHX)

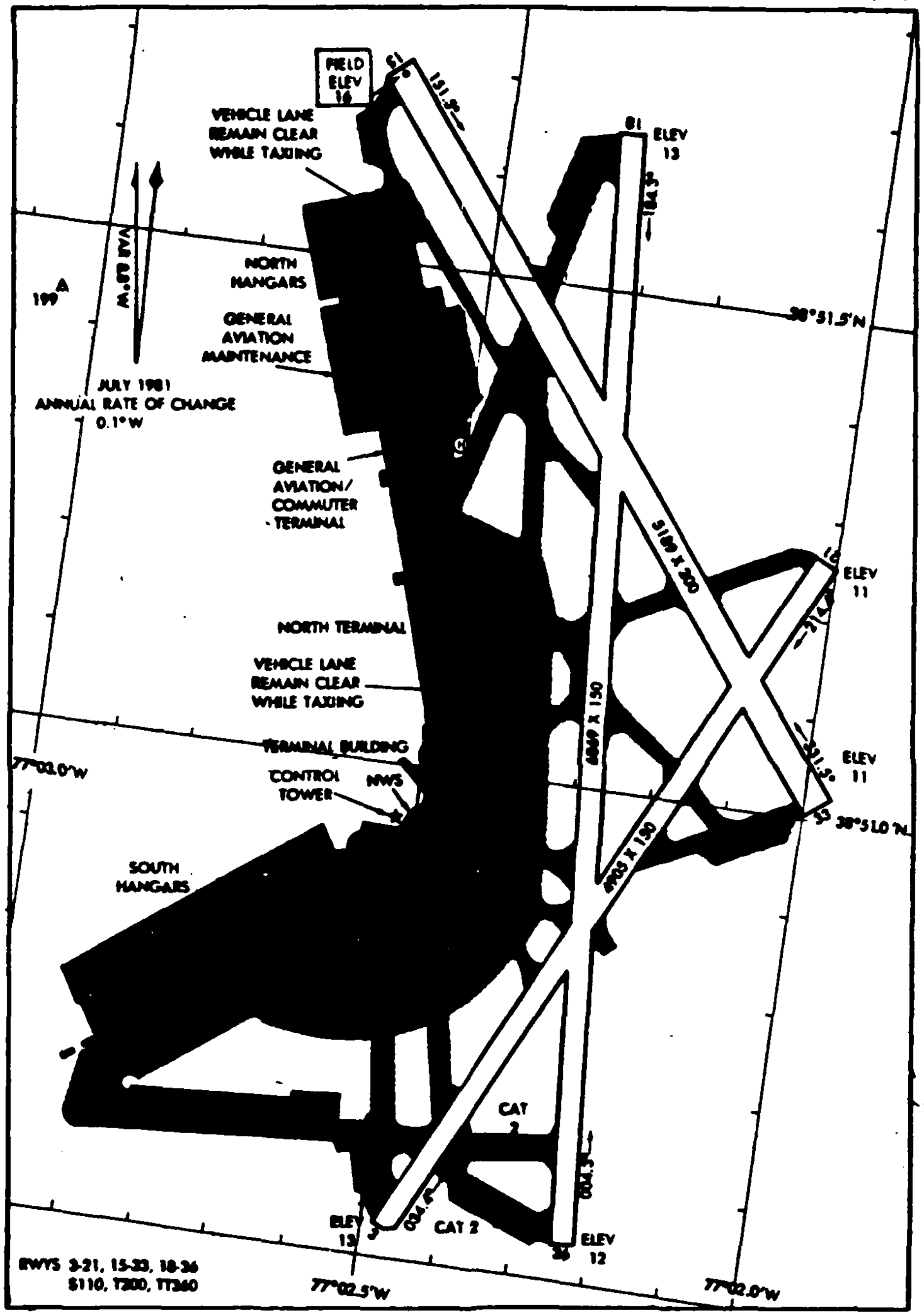
AIRPORT DIAGRAM



AIRPORT DIAGRAM

DETROIT METROPOLITAN WAYNE CO AIRPORT (DTW)

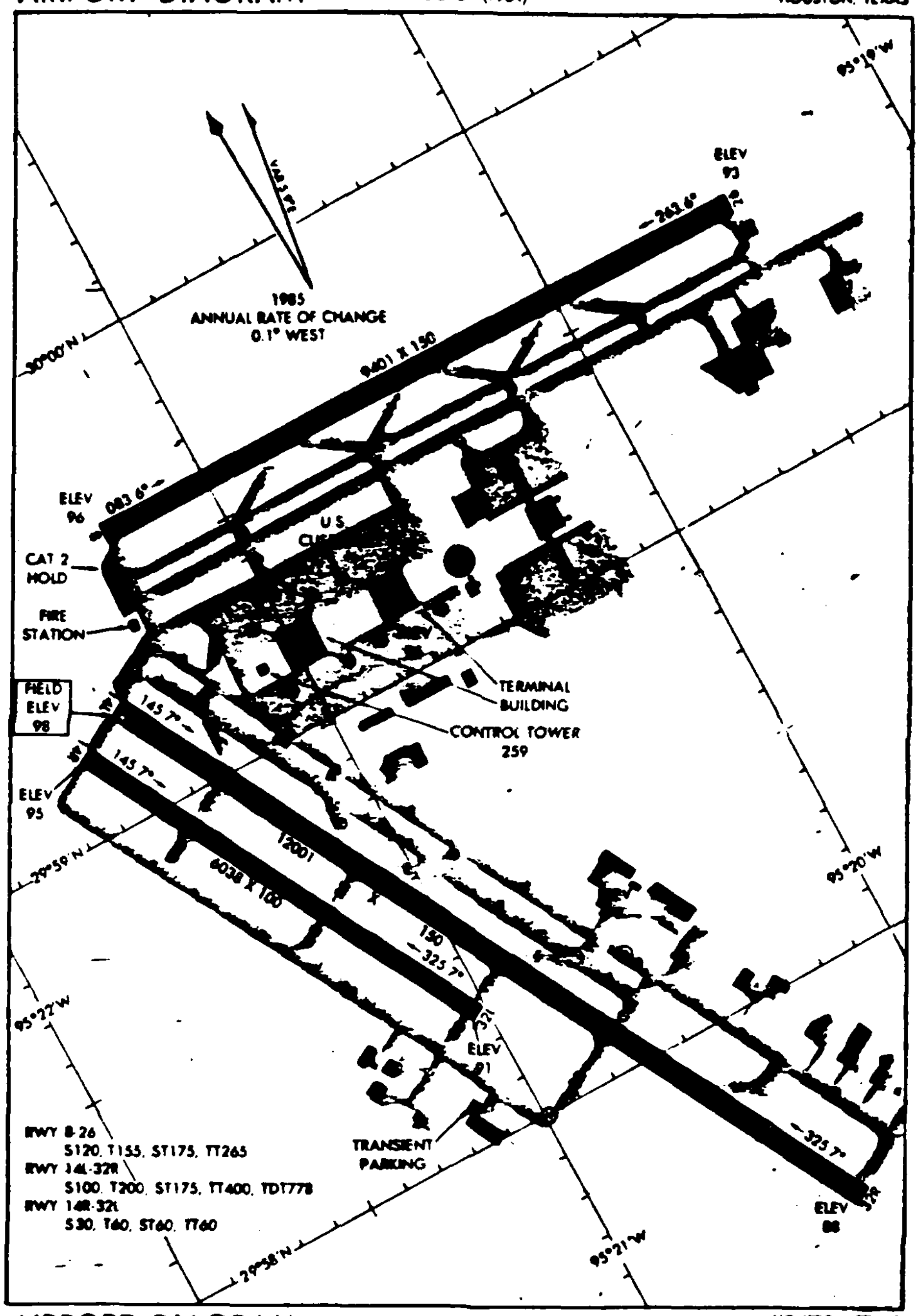
AIRPORT DIAGRAM



AIRPORT DIAGRAM

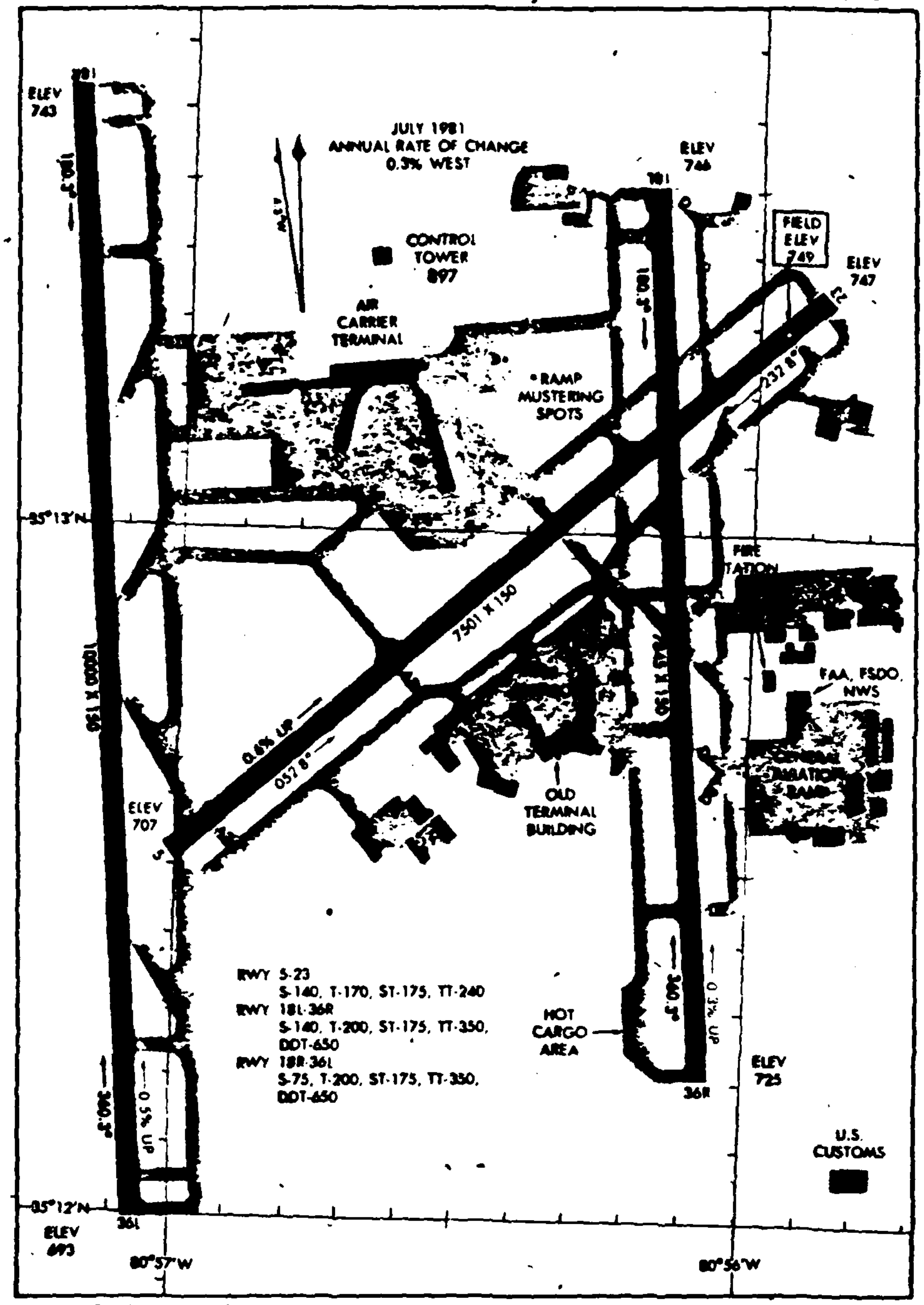
WASHINGTON, D.C.
WASHINGTON NATIONAL AIRPORT (DCA)

AIRPORT DIAGRAM 154 AL-5461 (FAA) **HOUSTON INTERCONTINENTAL (IAH)**
HOUSTON, TEXAS



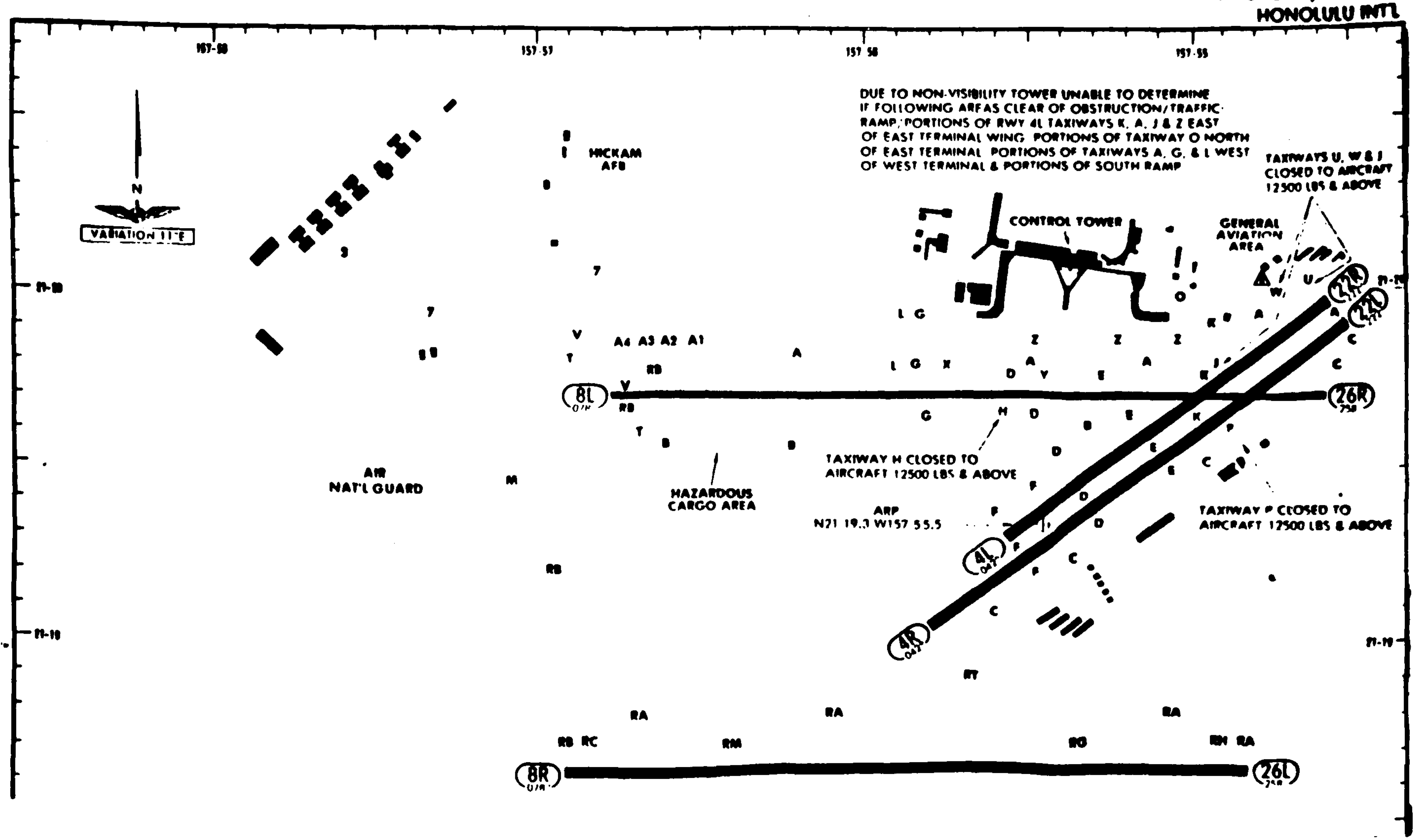
AIRPORT DIAGRAM HOUSTON, TEXAS
HOUSTON INTERCONTINENTAL (IAH)

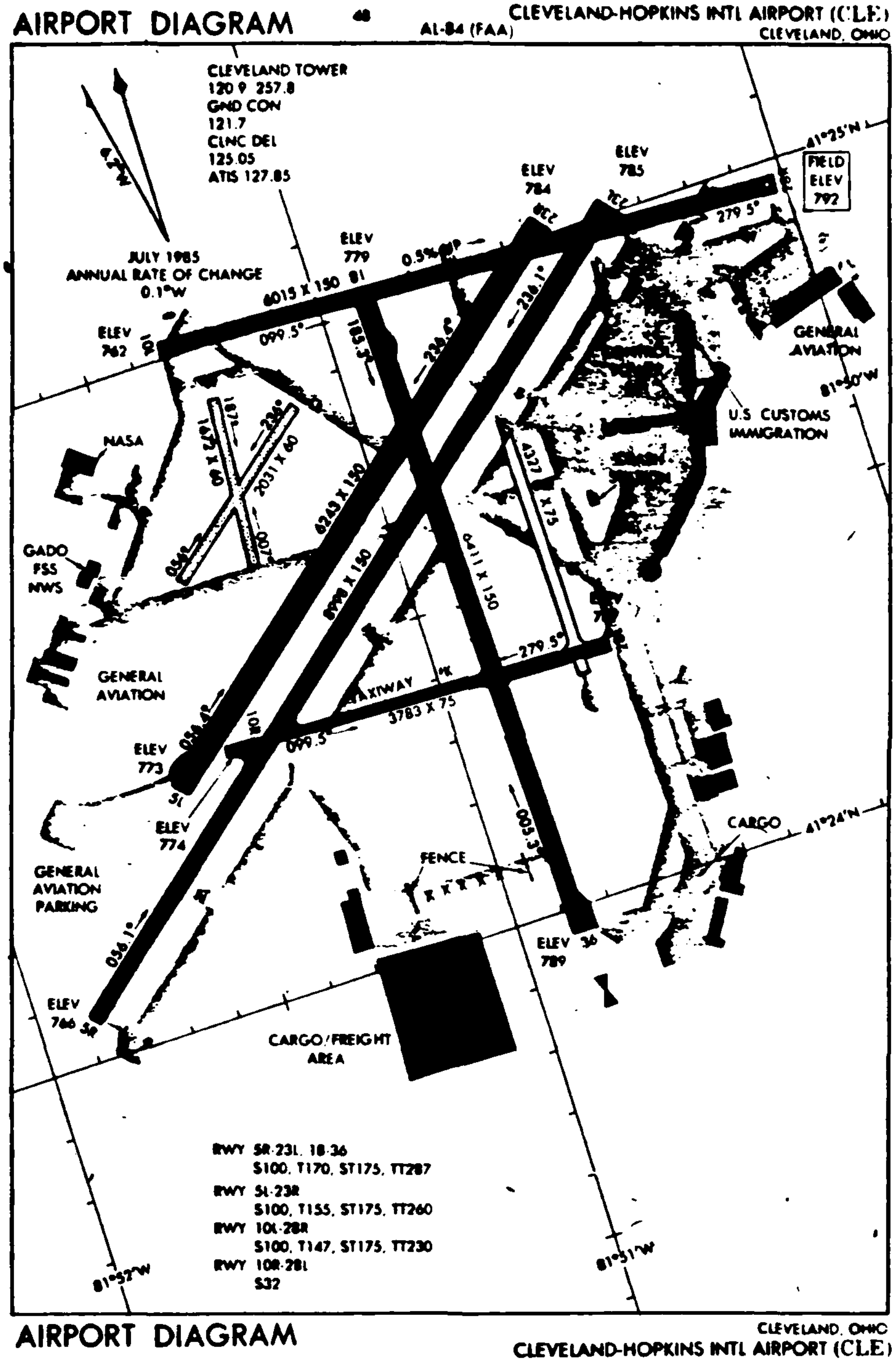
AIRPORT DIAGRAM AL-78 (FAA) CHARLOTTE/DOUGLAS INTL (CLT)
CHARLOTTE, NORTH CAROLINA



AIRPORT DIAGRAM 61 CHARLOTTE, NORTH CAROLINA
CHARLOTTE/DOUGLAS INTL (CLT)

HONOLULU, HAWAII
HONOLULU INT'L



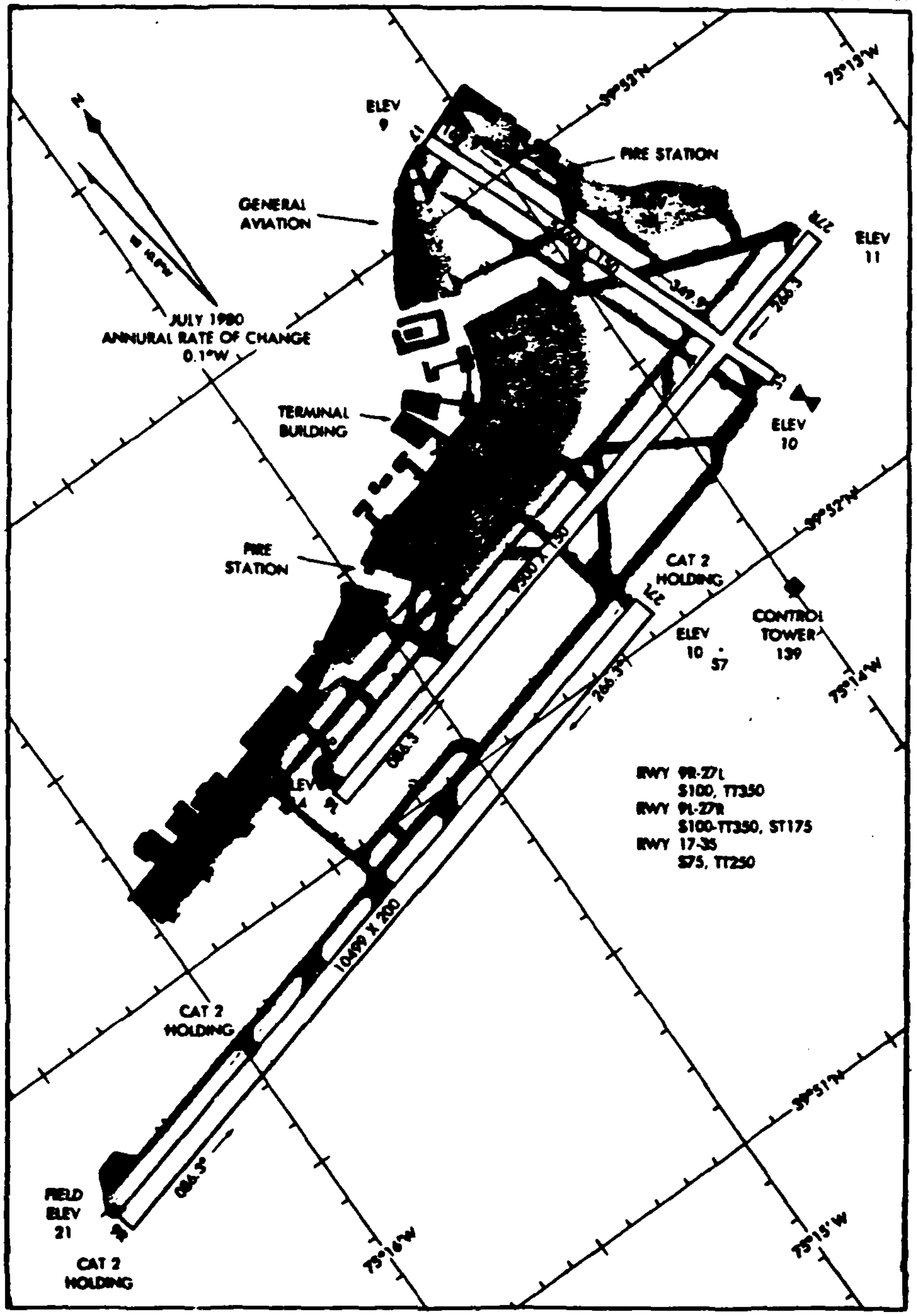

AIRPORT DIAGRAM
AL-84 (FAA)
CLEVELAND-HOPKINS INTL AIRPORT (CLE)
CLEVELAND, OHIO
CLEVELAND TOWER
120.9 257.8
GND CON
121.7
CLNC DEL
125.05
ATIS 127.85
JULY 1985
ANNUAL RATE OF CHANGE
0.1°W
FIELD
ELEV
792
ELEV
784
ELEV
785
ELEV
779
ELEV
762
6015 X 150
099.5°
279.5°
NASA
GADO
FSS
NWS
GENERAL
AVIATION
U.S. CUSTOMS
IMMIGRATION
6411 X 150
3783 X 75
TAXIWAY
ELEV
773
ELEV
774
GENERAL
AVIATION
PARKING
FENCE
CARGO
ELEV
789
ELEV
766
CARGO/FREIGHT
AREA
RWY 5R-23L, 18-36
S100, T170, ST175, TT287
RWY 5L-23R
S100, T155, ST175, TT260
RWY 10L-28R
S100, T147, ST175, TT230
RWY 10R-28L
S32
41°25'N
41°24'N
81°50'W
81°51'W
81°52'W
AIRPORT DIAGRAM
CLEVELAND, OHIO
CLEVELAND-HOPKINS INTL AIRPORT (CLE)

342

AIRPORT DIAGRAM

AL-320 (FAA)

PHILADELPHIA INTERNATIONAL (PHL)
PHILADELPHIA, PENNSYLVANIA



AIRPORT DIAGRAM

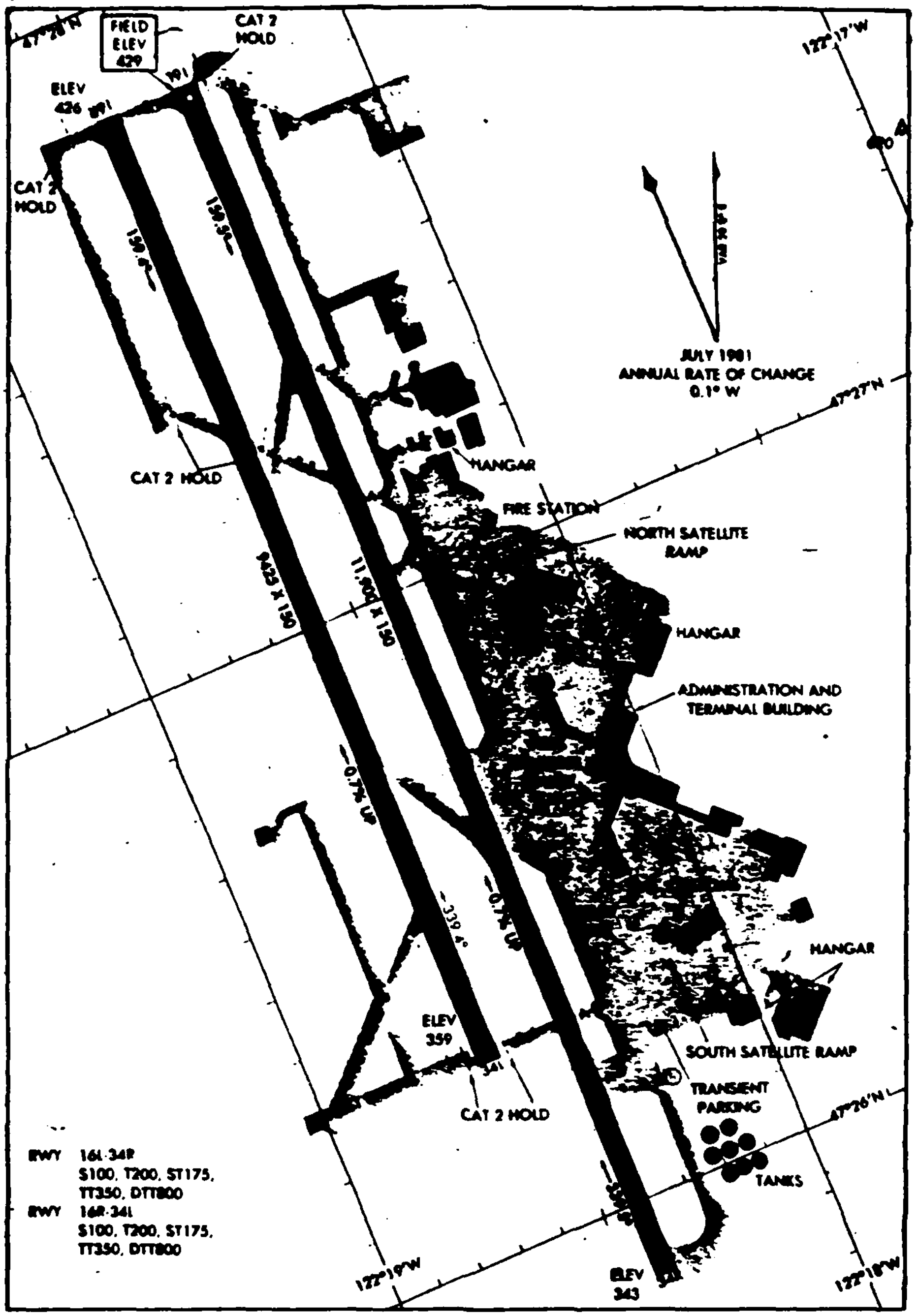
PHILADELPHIA, PENNSYLVANIA
PHILADELPHIA INTERNATIONAL (PHL)

382

AL-582 (FAA)

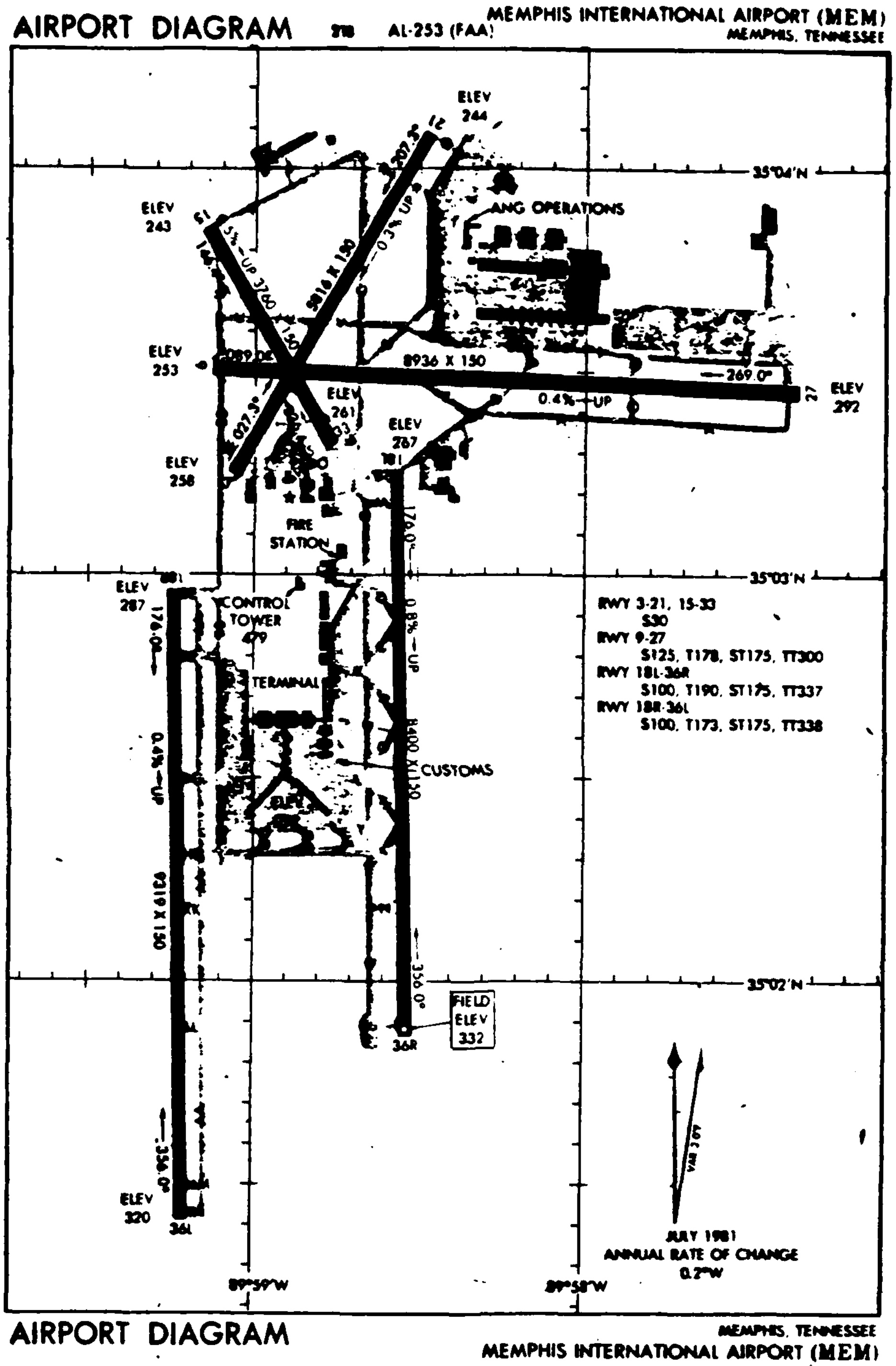
AIRPORT DIAGRAM

SEATTLE-TACOMA INTL (SEA)
SEATTLE, WASHINGTON

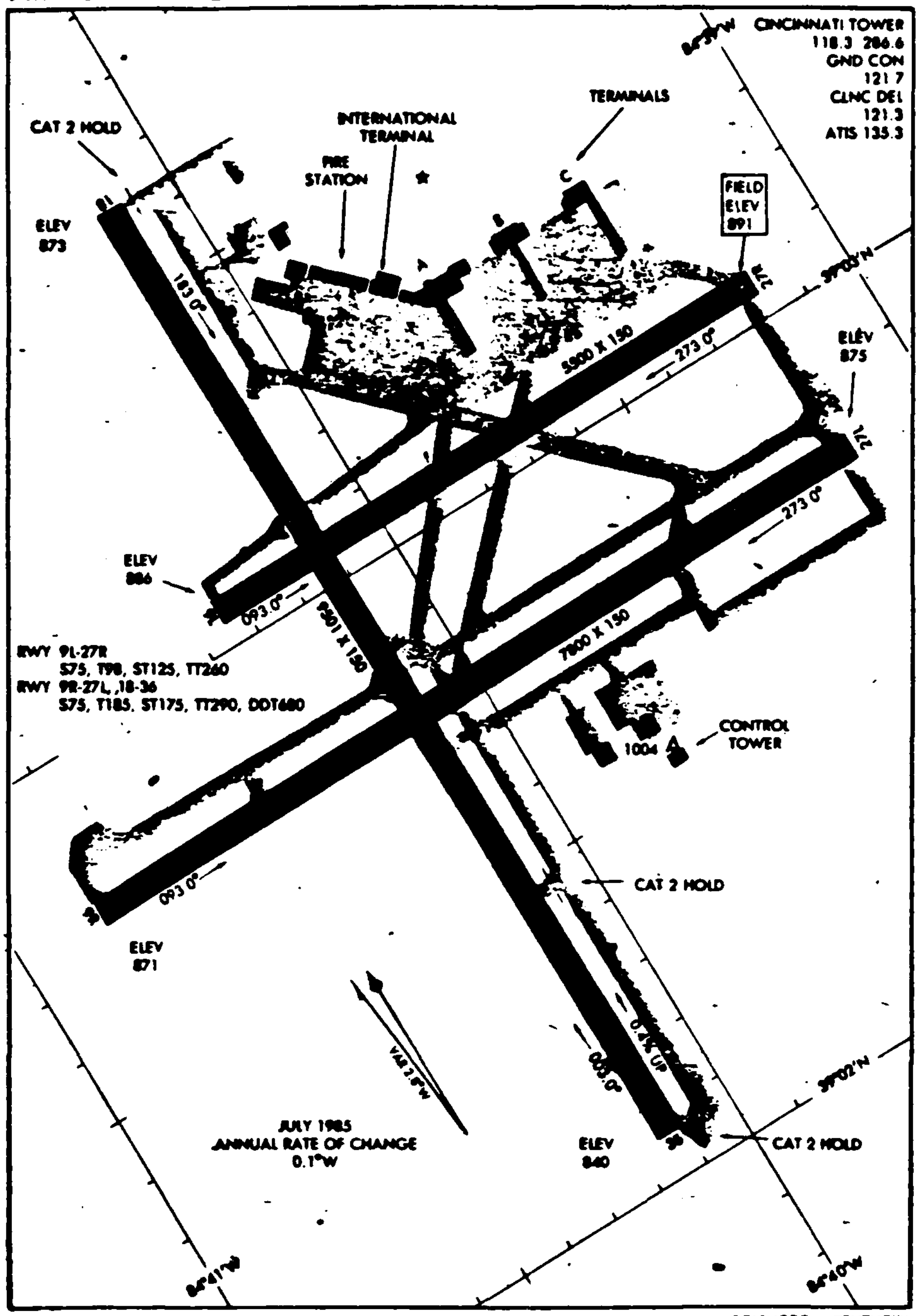


AIRPORT DIAGRAM

SEATTLE, WASHINGTON
SEATTLE-TACOMA INTL (SEA)


AIRPORT DIAGRAM
AL-253 (FAA)
MEMPHIS INTERNATIONAL AIRPORT (MEM)
MEMPHIS, TENNESSEE
ELEV 244
ELEV 243
ELEV 253
ELEV 258
ELEV 261
ELEV 287
ELEV 292
ELEV 320
ANG OPERATIONS
8936 X 150
0.4%—UP
FIRE STATION
CONTROL TOWER
TERMINAL
CUSTOMS
FIELD ELEV 332
36R
36L
35°04'N
35°03'N
35°02'N
89°59'W
89°58'W
RWY 3-21, 15-33
S30
RWY 9-27
S125, T178, ST175, TT300
RWY 18L-36R
S100, T190, ST175, TT337
RWY 18R-36L
S100, T173, ST175, TT338
JULY 1981
ANNUAL RATE OF CHANGE
0.2°W
AIRPORT DIAGRAM
MEMPHIS, TENNESSEE
MEMPHIS INTERNATIONAL AIRPORT (MEM)

AIRPORT DIAGRAM 62 AL-655 (FAA) COVINGTON/GREATER CINCINNATI INTL (CVG) COVINGTON, KENTUCKY



AIRPORT DIAGRAM COVINGTON, KENTUCKY COVINGTON/GREATER CINCINNATI INTL (CVG)

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DATE
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8-88
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